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PART I

Chapter 1

INTRODUCTION

1.1 Soil Structure Interaction Background

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

1.1.1 Literature Review

Regarding settlements and stresses of multi-layered soil systems, Burmister (2), (1) and Fox provided rigorous solutions for two-layered elastic systems and Burmister [9–13], Schiffman (3) Kirk (4) and Jones (5) revealed exact solutions for three-layered elastic systems.

For the immediate settlement classified as elastic deformation in soil–rock system, Ueshita (6), (7), (8) and Meyerhof (8), (7) exhibited the rigorous solutions which were employed to verify the availability of approximate solutions calculated by Steinbrenner's (9), (10) method. Furthermore, as for the immediate settlement of multi-layered soil systems, Ueshita and Meyerhof (7), (8) presented the rigorous solutions with which the approximate solutions given by Odemark's method were compared.

Palmer and Barber (11) proposed the approximate solution for two-layered elastic systems by the use of the equivalent thickness.

Using computational results provided by Burmister, Nascimento et al. propounded an approximate analytical method for pavements of multi-layered systems.

In Palmer et al.'s (11) method and Odemark's method, it is assumed that once multi-layered elastic systems with n-layers have been transformed into an equivalent single elastic layer, the calculation is only valid within the lowest layer n which is an isotropic and homogeneous material.

Ullidtz and Freeman and Harr presented that Odemark's method is able to approximate the multilayer theory of elasticity only for the case where elastic moduli of layers decrease with depth.

1.1.2 Standard methods of SSI analysis

Most of previous work began with the well-known Winkler model. The use of the Winkler model involves one major problem and one significant behavioral inconsistency. The problem involves the necessity for determining the modulus of subgrade reaction, "k," and the inconsistency is that an analysis of plates carrying a uniformly distributed load will produce a rigid body displacement.

The basic difference between Winkler and elastic foundations is that the Winkler deflections at a given node depend only on the forces at the node, while elastic deflections at a given node depends on the forces at the node and forces or deflections at other nodes.

- ELASTIC METHODS
- RIGID UNIFORM PRESSURE
- FINITE ELEMENT METHOD

1.2 Objectives and significance of this research

The aim of this research is to develop an automated analysis process regarding the effects of SSI to the behavior of shallow foundations under static loading that lay on elastic layered soil.

The procedure implemented for such purpose is called LSSI, Layered Soil Structure Interaction (12) and is a purely analytical approach to this problem. An important aspect of LSSI is that includes the variability of soil properties with depth determined from laboratory tests on soil specimens. Recent release of the Sap2000 OAPI (Open Application Programming Interface) from Csi Inc. has made feasible this effort providing also the benefit of creating a tool that would be of immediate access in most engineering offices.

The OAPI tool allows third-party developers to create rich and tight two-way links with SAP2000, for accurate transfer of models into SAP2000, complete control of SAP2000 execution, and extraction of analysis and design information from SAP2000, all from within their applications. The OAPI is compatible with most major programming languages, including Visual Basic Applications (VBA). Anyone familiar with Visual Basic programming should find the SAP2000 OAPI syntax easy and intuitive.

Before OAPI, a methodology based on a theoretical approach with various consecutive analysis procedures and algorithmic calculations had no practical use to routine engineering problems. Instead an automated process of the method would guarantee discretization precision, elimination of user errors and immediateness of results.

In this research using the API functions, has been implemented the LSSI procedure into a source code in Visual Basic programming language. Sap2000 imports the LSSI form as a plugin. The user after importing the structure in Sap2000 specifying the soil's geometric and elastic properties can execute the analysis. Even without any particular knowledge of the theoretical approach can retrieve information for the structure's settlement and solicitation state. The user after importing the structure in Sap2000 specifying the soil's geometric and elastic properties can execute the analysis. Even without any particular knowledge of the theoretical approach can retrieve information for the structure's settlement and solicitation state.

Chapter 2

SAP2000 APPLICATION PROGRAMMING

Facing the challenge of developing new, more accurate and, inevitably, more sophisticated procedures for the needs of structural engineering does not come at no cost; the need for computational power and the subsequent requirement to embrace tools and resources are demanding. The availability of increasingly productive computational systems that motivates the researchers to investigate more advanced and optimized tools for the assessment of structures, leads to development and adoption of new information technologies achievements. Furthermore, the need of simplifying the application of available procedures and making effective use of the computational methods already established is not to be neglected, as this can greatly improve the productivity and quality of performing every-day tasks. In this direction, the recently introduced computational tool SAP2000 API, which accompanies the structural analysis software SAP2000 of version 11, has come to significantly expand the usage of its parent-application into wider research fields beyond the structural analysis framework that currently exists.

2.1 Open Application Programming Interface (OAPI) for Sap2000

The SAP2000 Application Programming Interface (API) is a programming tool which aims to offer efficient access to the analysis and design technology of the SAP2000 structural analysis software, by allowing, during run-time, a direct bind to be established, between a third-party application and the analysis software itself [Fig. 1]. Additionally, through the use of this API,

one has the option of developing plug-ins, which extend the program's usability and are totally embedded within the SAP2000 environment. In terms of computer programming, the API consists of a software library that offers access to a collection of objects and functions capable of “remotely” controlling the way that the SAP2000 behaves, thus, overriding the standard point-and-click procedure. Highlights of the main features that the API provides are summarized below:

- Direct, fast and robust coupling with the SAP2000 design and analysis methods.
- Two-way data flow as it can be used to facilitate both pre- and post-processing procedures.
- No need of using intermediate files, which reduces significantly the time needed for data exchange when working on large models.
- Compatibility with most major programming languages.
- Concurrent data transfer and control of a structural model by different third-party applications.
- Development of third-party applications that will remain compatible with future releases of SAP2000.
- Ability to develop a custom interface for SAP2000, calibrated to the user's needs, or to embed one in an application that allows for user programming.:

In order to make use of the above SAP2000 API features for developing new computing tools, usually a solid programming background is required, as the process may prove demanding, in terms of programming skills. However, this is not always the case, when it comes to simple computing tasks. In either case, the SAP2000 API offers a broad range of programming languages that it can be used which cover the vast majority of the modern software development options including Visual Basic.NET, Visual Basic for Applications (VBA), Visual C#, Visual C++, Visual Fortran and Matlab. To get started with, accessing the API requires nothing more than a functional SAP2000 installation, as all the components that it consists of are automatically installed during the main program's setup. Using it, however, depends at large on the programming language that the developer is familiar with and the programming environment that is selected for this purpose. Different integrated development environments (IDEs) offer several options in order for the programming project to link successfully with the API and, additionally, in each case the syntax to be used and the potential planning of the application to be developed differ according to the language's standards. One should bear in mind, however, that in order to make effective use of the API it may be appropriate that the

programming style, to which one is accustomed to, has to be adapted to the way the API is structured, due to its non-deviant attitude, regarding the SAP2000 approach to designing an assessing a structure; in any case though, the steps necessary to accomplish a task via the API resemble vastly the corresponding point-and-click procedure required by the standard usage of the parent-application.

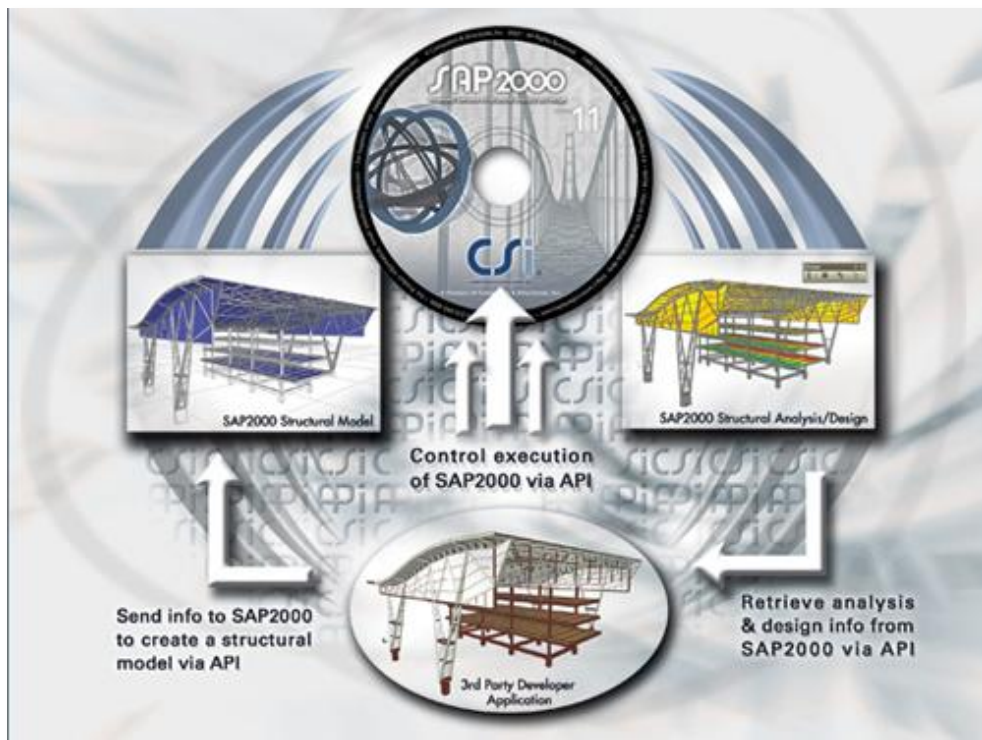


Figure 1 Typical dataflow using the SAP2000 API

As a general assistant in utilizing the SAP2000 API, a detailed documentation file is also provided along with the installation (SAP2000_API_Documentation.chm) including all the required information that will assist in getting accustomed to the API programming. This guide is to be used side-by-side when developing SAP2000 collaborated software, as it contains a full list of every single function provided, accompanied by its exact syntax, a detailed description of the arguments that it handles and a commented example of usage.

Chapter 3

THEORETICAL APPROACH OF THE LSSI PROCEDURE

3.1 Supporting the structure

Before describing the theory on the basis of the LSSI procedure a reference on how the structure is supported must be made. The discretized foundation is simply supported in its contact nodes with the soil. Supported points of the foundation are divided into two groups. The first group contains the internal supported points “ISP” of the structure that refers to the active nodes that are in contact with the soil. The second group refers to the external supported points “ESP” that are the peripheral inactive nodes of the foundation. The restraints assigned for these two groups of supported points are the following:

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

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

* assuring that no horizontal movements of the foundation would occur

3.2 Deformational behavior of elastic soil under vertical loads

3.2.1 Settlement calculation based on theory of elasticity

STEINBRENNER'S THEORY (1934)

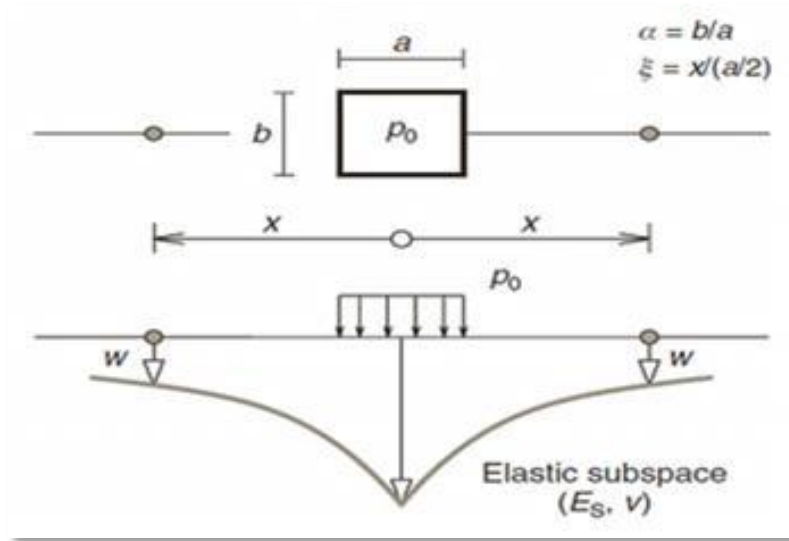


Figure 2 Settlement due to load on surface of elastic layer, Method of estimating settlement (After Steinbrenner, 1934)

This theory determines immediate settlement w of the soil at the edge of a rectangle area $a \times b$ under uniformly distributed vertical load P_0 . The deformable layer has depth z and elastic properties the modulus of elasticity E and the Poisson's ratio ν .

$$w(a, b) = f(z)/Y$$

where:

$$Y = E/(1 - \mu^2)$$

$$f(z) = \frac{ap}{4\pi} \left[\zeta \cdot \arctan\left(\frac{\beta}{\zeta\gamma}\right) + \ln\left(\frac{\gamma - \beta}{\gamma + \beta} \cdot \frac{\omega + \beta}{\omega - \beta}\right) + \beta \cdot \ln\left(\frac{\gamma - 1}{\gamma + 1} \cdot \frac{\omega + 1}{\omega - 1}\right) \right]$$

$$\beta = b/a, \quad \zeta = 2z/a, \quad \omega = \sqrt{1 + \beta^2}, \quad \gamma = \sqrt{1 + \beta^2 + \zeta^2}$$

STAVRIDIS' THEORY (2002)

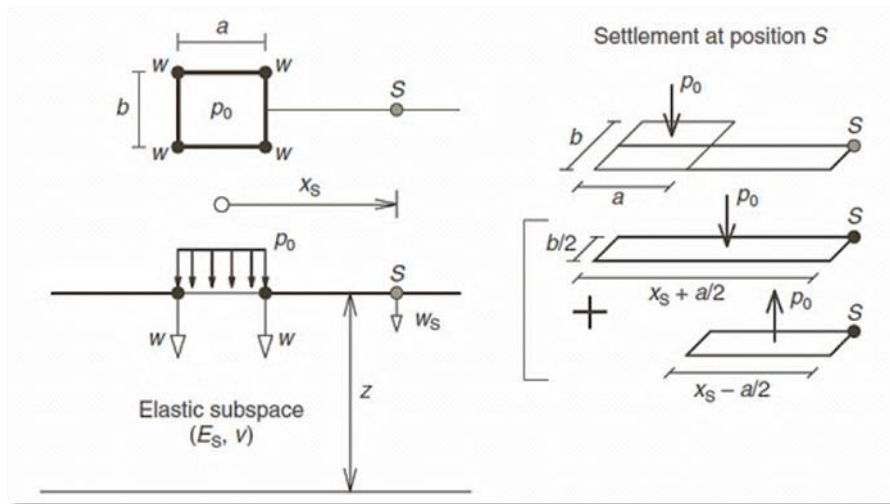


Figure 3 Settlement of an orthogonal area over a soil layer of finite thickness

Using a load superposition method as shown in Figure 3 the following equation occurs, determines settlement developed at a point of the soil outside of the loaded area, at a distance x_s and y_s from its center.

$$w_s = w(x_s + a/2, y_s + b/2) - w(x_s - a/2, y_s + b/2) - w(x_s + a/2, y_s - b/2) + w(x_s - a/2, y_s - b/2)$$

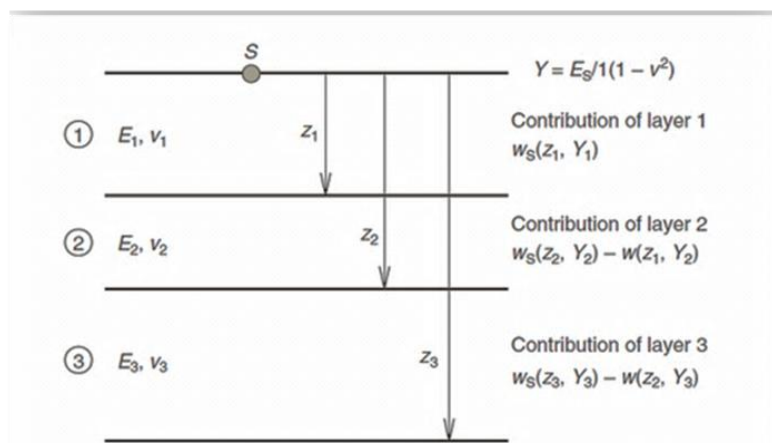


Figure 4 Multi layered soil, settlement of point s results from superposition of all layers contribution

Soil profile could have more layers with properties determined from geotechnical investigation. With the following equations settlement could be calculated for this case too. Contribution to settlement from each layer is considered.

$$w_{s,i}(Y_i) = w_s(z_i, Y_i) - w_s(z_{i-1}, Y_i)$$

$$w_s = w_{s,1}(Y_1) + w_{s,2}(Y_2) + \dots + w_{s,k}(Y_k)$$

$$w_s = f(z_1)(1/Y_1 - 1/Y_2) + f(z_2)(1/Y_2 - 1/Y_3) + \dots + f(z_{k-1})(1/Y_{k-1} - 1/Y_k) + f(z_k)(1/Y_k)$$

3.3 Deformability matrix of layered soil

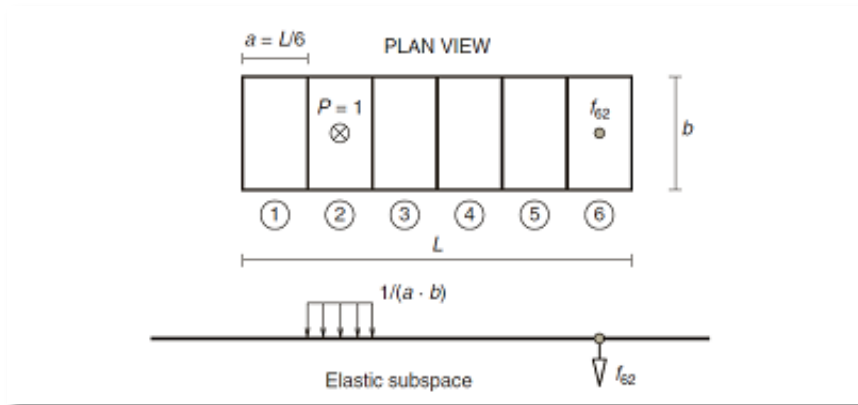


Figure 5 Influence of a loaded area on the settlement of a point lying on the soil surface

A strip of length L and constant width b is considered and is divided into a number of n equal segments of length (L/n) as shown in Figure 5, whereby a mutual deformational influence of each of the above elements on the others is sought. Applying a unit vertical load $P = 1$ consecutively on the midpoint of each element and assuming it to be uniformly distributed over that segment with an intensity P_0 :

$$P_0 = \frac{1}{(L/n) \cdot b}$$

A number of n_2 settlements f_{si} may be determined. Those represent the settlements that develop in the element number s when the element i is loaded with $P_i = 1$ and quantities f_{11}, f_{12}, \dots may be directly determined.

The above deformations allow the determination of settlement for static loading at all midpoints. The settlement w of each segment is respectively:

$$\left\{ \begin{array}{l} w_1 = f_{11} \cdot P_1 + f_{12} \cdot P_2 + \dots + f_{1n} \cdot P_n \\ w_2 = f_{21} \cdot P_1 + f_{22} \cdot P_2 + \dots + f_{2n} \cdot P_n \\ \vdots \\ w_{n-1} = f_{n-11} \cdot P_1 + f_{n-12} \cdot P_2 + \dots + f_{n-1n} \cdot P_n \\ w_n = f_{n1} \cdot P_1 + f_{n2} \cdot P_2 + \dots + f_{nn} \cdot P_n \end{array} \right.$$

By assembling settlements ' f ' in a square matrix $[F]$ ($n \times n$) the flexibility matrix is derived.

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

$$\{\Delta_{soil}\} = [F_{soil}] \cdot \{P_{soil}\}$$

3.4 Stiffness matrix of foundation support

Considering the beam in the previous figure the contact surface is assumed to be simply supported at the above n midpoints. Imposing on the first support a unit displacement $s_1 = 1$ a set of self-equilibration reactions $k_{11}, k_{21}, \dots, k_{n1}$ is developed. Proceeding consecutively to the other supports the following relations are obtained:

$$\left\{ \begin{array}{l} R_1 = k_{11} \cdot \Delta_1 + k_{12} \cdot \Delta_2 + \dots + k_{1n} \cdot \Delta_n \\ R_2 = k_{21} \cdot \Delta_1 + k_{22} \cdot \Delta_2 + \dots + k_{2n} \cdot \Delta_n \\ \vdots \\ R_{n-1} = k_{n-11} \cdot \Delta_1 + k_{n-12} \cdot \Delta_2 + \dots + k_{n-1n} \cdot \Delta_n \\ R_n = k_{n1} \cdot \Delta_1 + k_{n2} \cdot \Delta_2 + \dots + k_{nn} \cdot \Delta_n \end{array} \right.$$

By assembling reactions 'k' in a square matrix $[K]$ ($n \times n$) the stiffness matrix is derived. The above system can be written in a matrix form:

$$\{R_{SUP}\} = [K_{SUP}] \cdot \{\Delta_{SUP}\}$$

3.5 LSSI procedure

The major steps of the process are:

- Finite discretization of the structure considered, whereby an orthogonal layout for the foundation element nodes should be used.
- Reference of the foundation meshing to the soil surface through the respective n nodes and determination of the soil stiffness matrix K_{soil} through consecutive loading of the surface nodes.
- Determination of the n reaction forces of the simply supported model under the given loading and consequent assembly of the column matrix R_o
- Through consecutive setting of unit support settlement to each one of the N points of support, determination of the respective reaction forces of the simply supported model and assembly of the support stiffness matrix K_{sup} .
- Determination of the displacements Δ of the foundation nodes.
- Determination of the state of stress in the simply supported model under the external loading and the imposing of the calculated support settlements Δ .
- Determination of the soil pressures.

3.6 Equation solution

The analysis of LSSI procedure can be described in terms of equations as it follows:

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

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

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

$$\stackrel{(2)}{\Rightarrow} \{R_o\} - \{R_{SUP}\} = \{R_o\} + [K_{SUP}] \cdot \{-\Delta_{SUP}\} \quad (4)$$

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

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

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

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

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

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

Chapter 4

ALGORITHM IMPLEMENTATION IN A VB SOURCE CODE

Implementing an innovative scientific method requires thorough planning and well balanced decisions to be made, regarding the usability, flexibility and layout of the final product. Developing software capable of applying the LSSI procedure to structures involves taking into account a considerable amount of analysis parameters, storing and manipulating a large number of variables and ensuring that access is granted to important information at every stage of the analysis.

4.1 Software Architecture

4.1.1 Visual Basic for Applications

Visual Basic for Applications (VBA) is an implementation of Microsoft's event-driven programming language Visual Basic 6 and its associated integrated development environment (IDE).

Visual Basic for Applications enables building user-defined functions, automating processes and accessing Windows API and other low-level functionality through dynamic-link libraries (DLLs). It can be used to control many aspects of the host application, including manipulating user interface features, such as menus and toolbars, and working with custom user forms or dialog boxes.

As its name suggests, VBA is closely related to Visual Basic and uses the Visual Basic Runtime Library, but it can normally only run code within a host application rather than as a standalone program. It can, however, be used to control one application from another via OLE Automation. VBA has the ability to use DLLs, and later versions add support for class modules.

VBA is built into most Microsoft Office applications, including Office for Mac OS X and other Microsoft applications such as Microsoft MapPoint and Microsoft Visio, as well as being at least partially implemented in other applications such as ArcGIS, AutoCAD, CATIA, WordPerfect and Sap2000.

Interaction with the host application uses OLE Automation. Typically, the host application provides a type library and application programming interface (API) documentation which documents how VBA programs can interact with the application. This documentation can be examined from inside the VBA development environment using its Object Browser.

Multiple applications can be automated from the one host by creating Application objects within the VBA code. References to the different libraries must be created within the VBA client before any of the methods, objects, etc. become available to use in the application. These application objects create the OLE link to the application when they are first created. Commands to the different applications must be done explicitly through these application objects in order to work correctly.

4.2 Description of the implementation

The scheme chosen, so as to implement the LSSI method, consists of an application arranged in modules, separated according to the tasks that are intended to perform. The analysis flow is controlled through an interactive graphical user interface (GUI), which consists of a main window that contains all the components necessary to define and review the analysis procedure. The pre and post-processing is made entirely inside a separate dynamic link library (DLL) that binds the interface with the SAP2000 software. This is accomplished through the use of the SAP2000 OAPI, which aims to regulate the flow of data.

The user is expected to interact entirely with the interface provided, while SAP2000 runs silently in the background of the operating system's desktop, throughout the analysis runtime.

What is more, the required actions related to the manipulation of the SAP2000 model file are transferred, via the API, to the LSSI software's interface. However, if needed, the user is allowed to bring the SAP2000 interface to the foreground, in order to make explicit definition of any advanced parameters that the LSSI software does not provide, gaining, thus, complete control over the procedure.

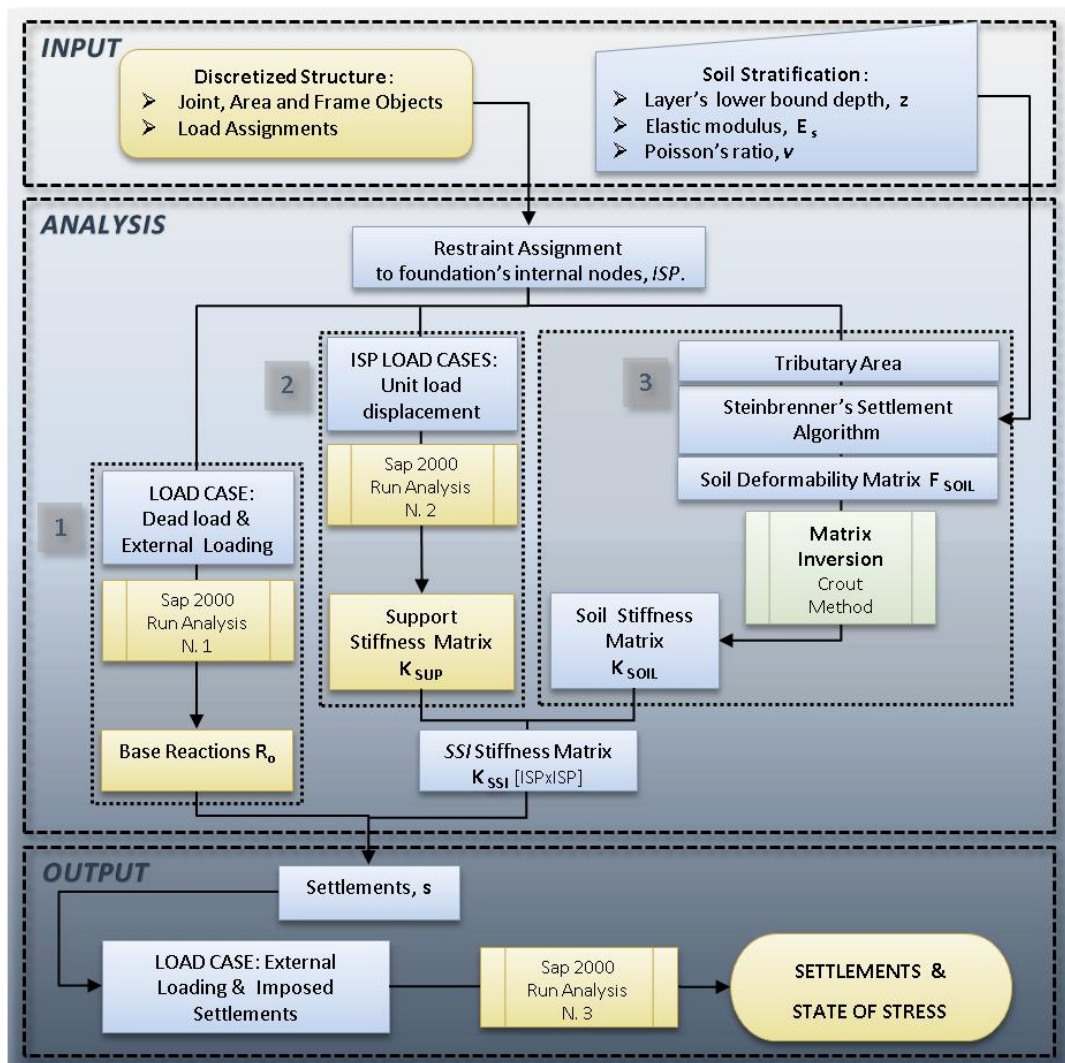


Figure 6 Flow chart of the LSSI analysis process

The code starts by storing the input data required to perform the LSSI. 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, Figure 7.

Also their tributary area is determined as shown in the figure below. A tributary area is an equivalent rectangular area of influence of each contact node that will call later the process to determine soil deformability.

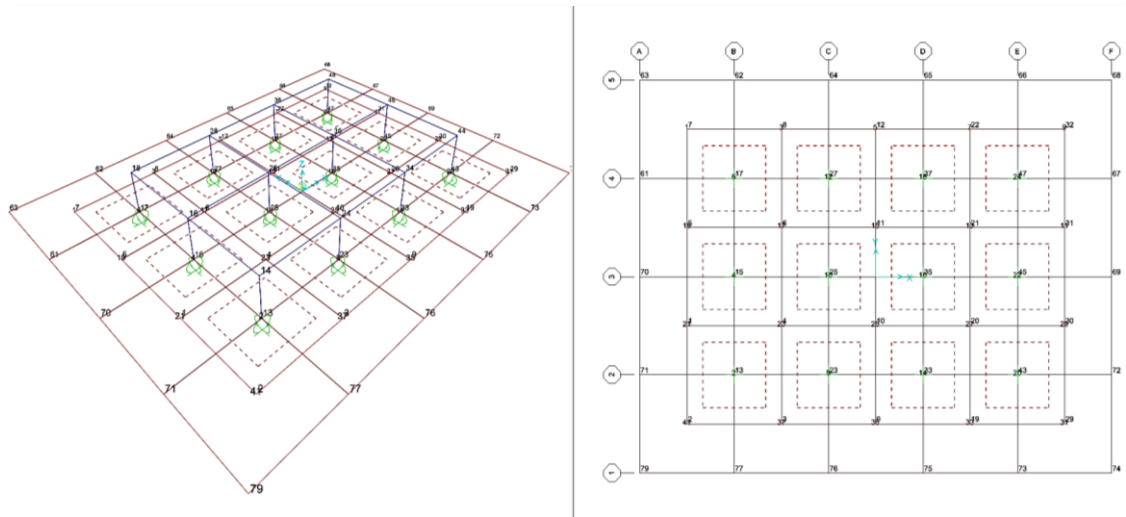


Figure 7 Tributary areas of each foundations supported node

The procedure LSSI begins with retrieving the reactions of foundation R_0 for a simple analysis of the 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 is imposed a unit load displacement and are retrieved the reactions of the foundation to this settlement that will fill a column of the stiffness matrix, Figure 8.

The soil stiffness matrix is determined by inversion, calculating the deformability matrix with an analytical algorithm. To each contact node is imposed this time a unit load. From

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. These settlements will fill a row of the deformability matrix.

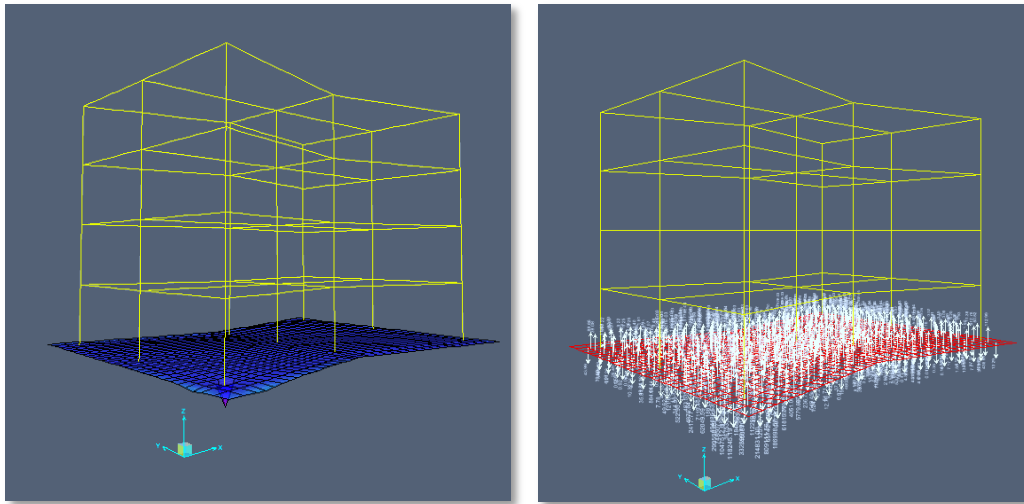


Figure 8 Load Case: Unit Load Displacement and reactions

At this point the procedure can solve the linear problem presented in the following equation and determine the foundation's settlements.

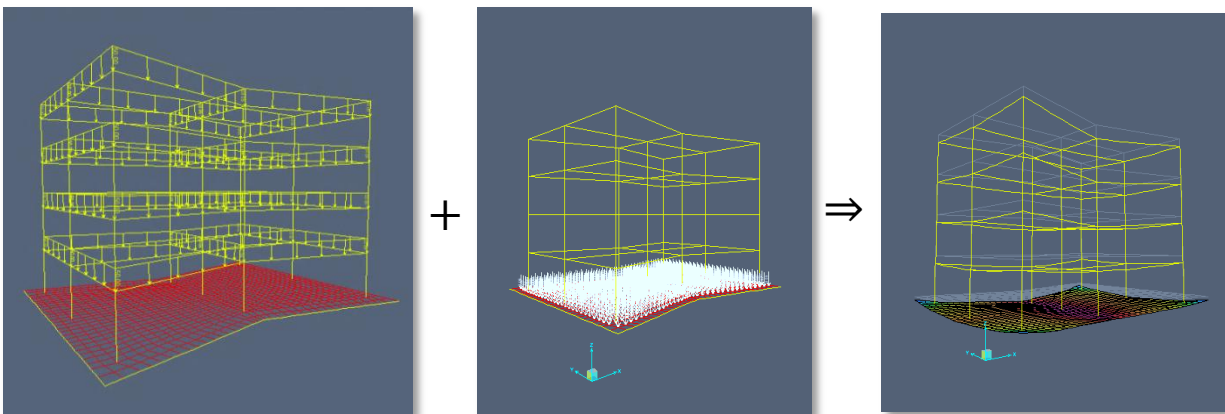


Figure 1 Assigning the derived settlements to the contact nodes of the foundation (soil deformability) the LSSI procedure can analyze the response of the system soil structure under static loading

PART II

Chapter 5

NUMERICAL EXAMPLES

5.1 Shallow Foundations

A shallow foundation is a type of foundation which transfers building loads to the earth very near the surface, rather than to a subsurface layer or a range of depths as does a deep foundation. Shallow foundations include mainly grade beam foundations and mat-slab foundations. The LSSI procedure for analysis of a shallow foundation, such as plate or beam foundation, on elastic soil requires geotechnical investigations to assist evaluation of reasonable values for soil input parameters. These parameters include the elastic soil modulus and Poisson's ratio for the plate on elastic foundation, and depth of the lower bound of each layer.

5.2 Case Study: Mat Foundation

5.2.1 Model Description

STRUCTURE

The concrete structure in Figure 7 consists of an upper slab with a rectangular hole located in its loads to four peripheral walls and four inner columns resting on a continuous foundation slab. 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.

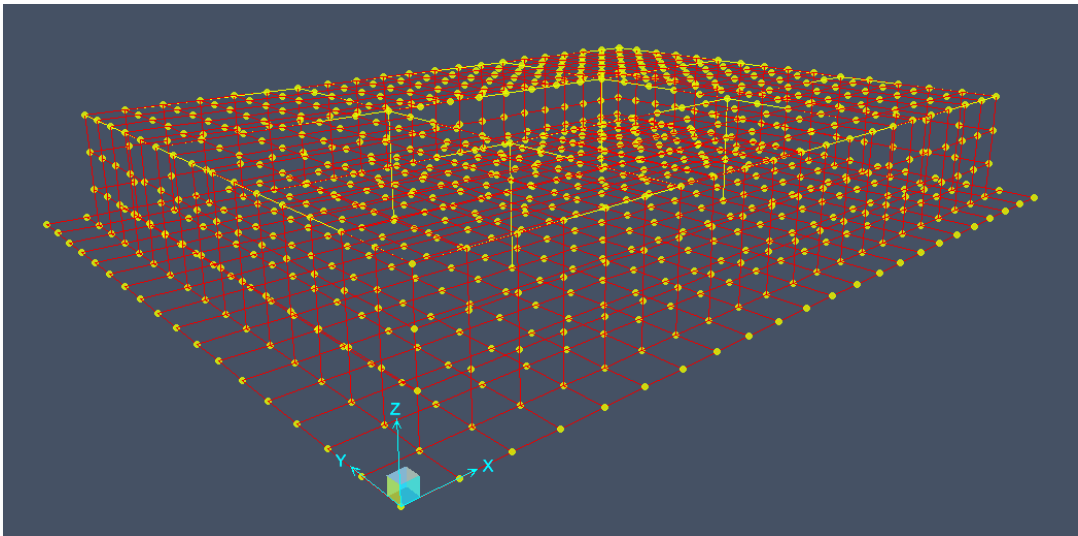


Figure 10 Mat Slab Foundation

LOAD PATTERN

The upper plate is loaded with a uniform load of 20 kN/m^2 and moreover four concentrated loads each one of 1.500 kN are applied at the top of the four columns.

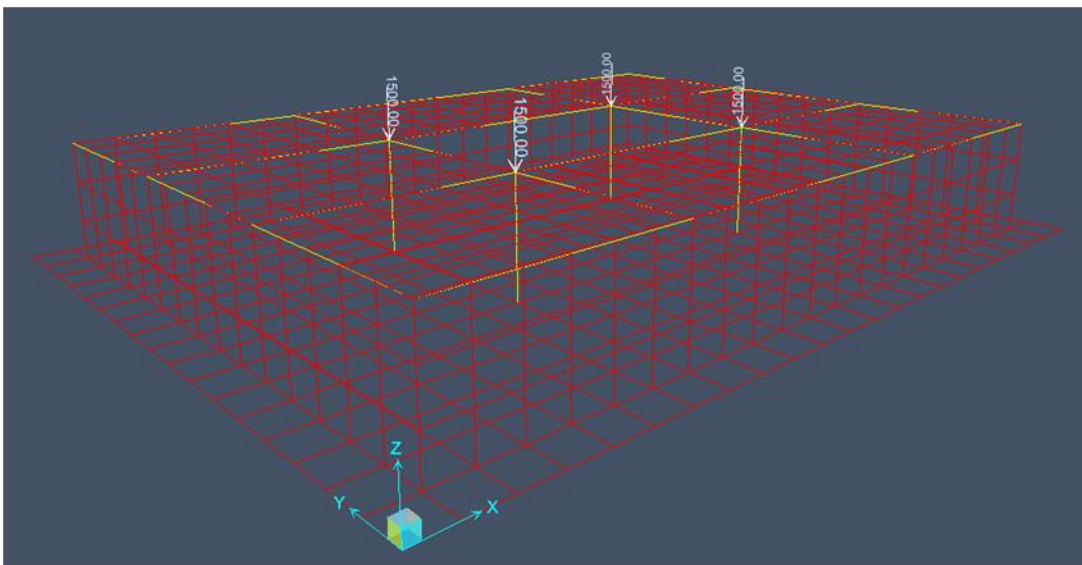


Figure 11 Concentrated Loads

SOIL

The profile of the foundation soil consists of three horizontal layers of distinct elastic characteristics resting on a hard rock underground. The elastic moduli of the layers and the

respective depths are shown in Figure 8. The Poisson's ratio is taken for all layers equal to 0,3.

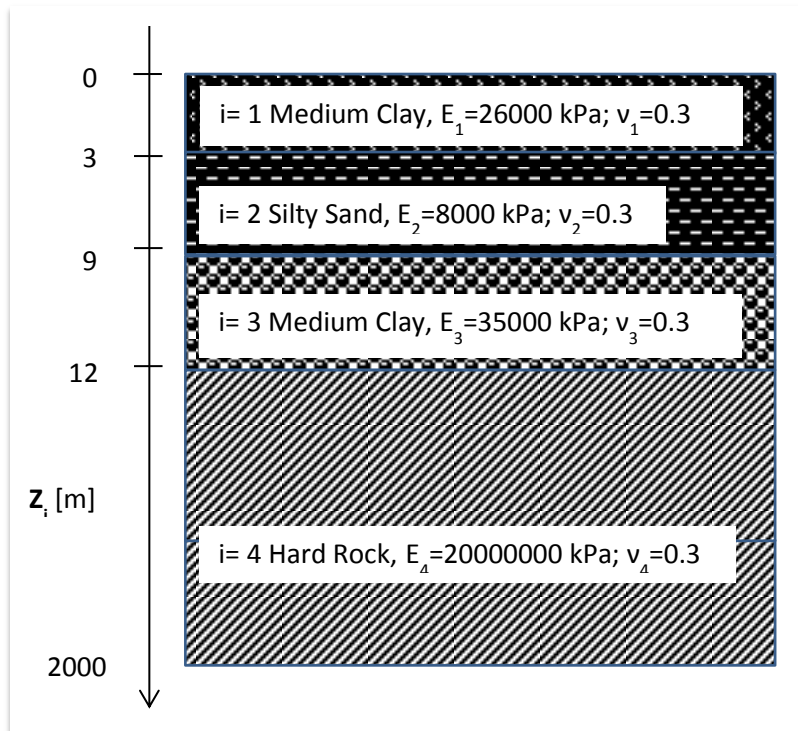


Figure 2 Soil profile

5.2.2 Discretization in Sap2000

The discretization of the foundation plate is shown Figure 7 according to which the whole structural model is simply supported on the resulting 336 contact nodes.

5.2.3 Output Analysis Results

The results obtained with the procedure LSSI are presented in the following images. The response of the structure regarding settlements is shown in Figure 10, Figure 11, Figure 12.

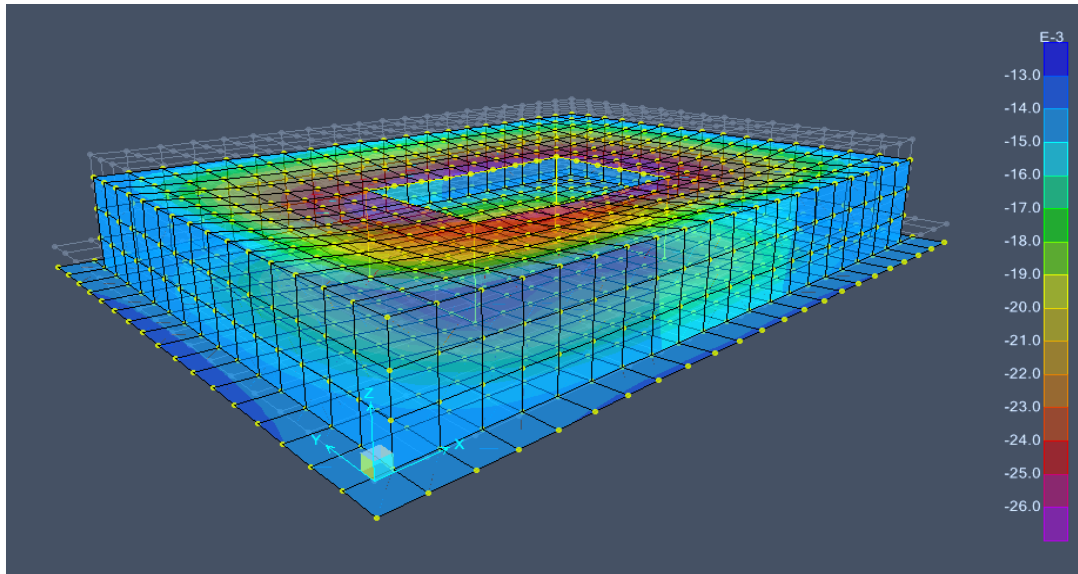


Figure 13 Structure's deformed shape [m]

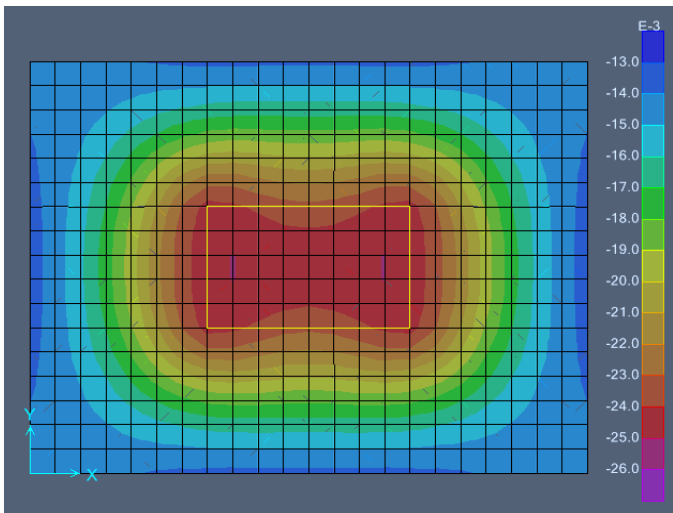


Figure 3 Foundation slab settlements[m]

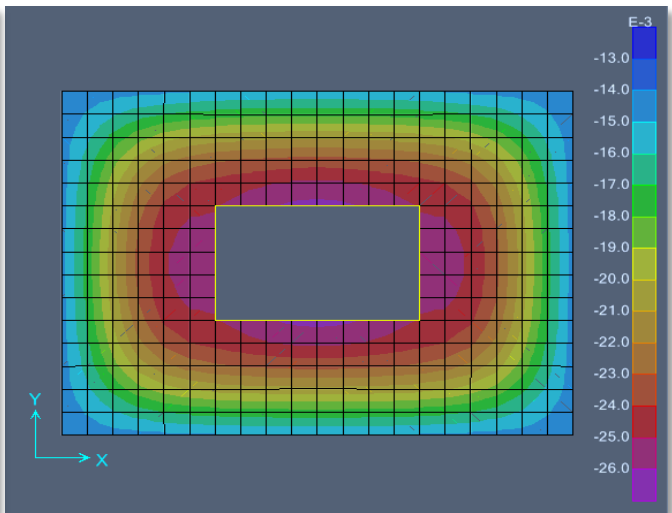


Figure 4 Upper plate settlements[m]

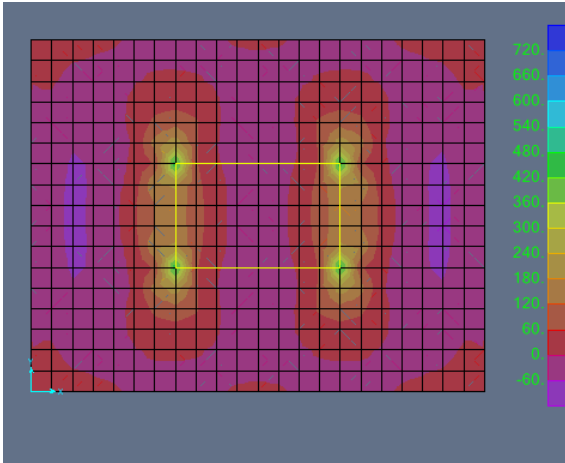


Figure 16 Foundation Moments, F11 [kNm/m]

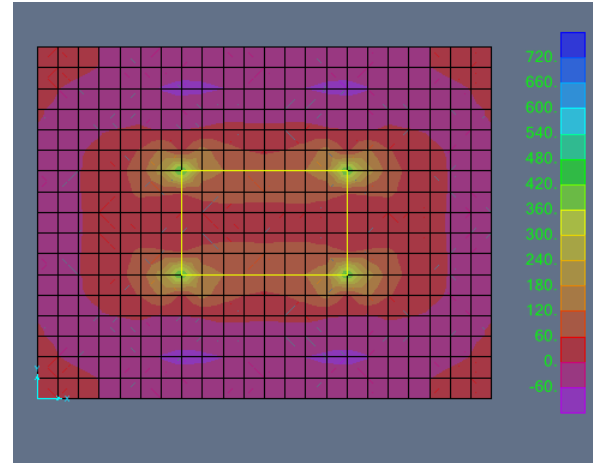


Figure 17 Foundation Moments, F22 [kNm/m]

5.2.4 Comparison of results, LSSI vs. Winkler's model

For comparison purposes, the results for a modulus of subgrade reaction k_s equal to 21.730 kN/m^3 are also presented. This value is derived as $k_s = 1/w_s$, where w_s is the settlement of the centroid of a square area of 1 m^2 loaded with 1 kN/m^2 over the actual profile. This settlement may be calculated from eq. which in this case turns out to be $4,60 \cdot 10^{-5} \text{ m}$. Comparison to the Winkler's method gives information whether the predicted settlements and state of stress are in agreement to those obtained from other methods and to make conclusions whether the LSSI procedure underestimates or not the deformational behavior of the interface foundation – soil, knowledge that make able the designer to deduct decisions the structure's design.

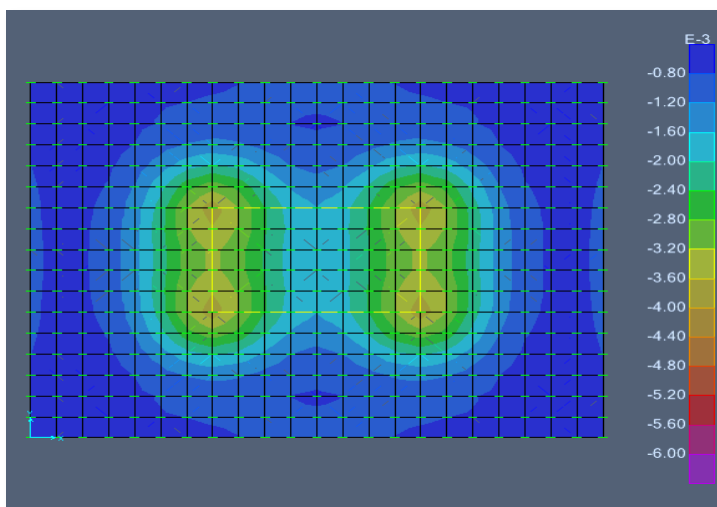


Figure 5 Foundation settlements with Winkler's method

Foundation slab – x axis	Section I-I		M _x [kNm/m]	
Place	I1	I2	I3	I4
Elastic Subspace	65.9	13.5	-161.4	34.5
Winkler's method	11.5	57.50	-119.4	74.4
LSSI	-43.74	-15.80	156.69	-30.24

Foundation slab – y axis	Section II-II		M _y [kNm/m]	
Place	I1	I2	I3	I4
Elastic Subspace	58.8	6.4	-82.6	-57.7
Winkler's method	4.17	43.5	-11.0	-20.0
LSSI	-26.91	7.54	87.13	52.68

Bending moments of foundation beams M [kNm/m]				
Place	I1	I2	I3	I4
Elastic Subspace	-454.5	134.9	-360.9	3.79
Winkler's method	-483.0	193.6	-391.8	143.60
LSSI	296.44	-149.29	221.50	13.68

Figure 6 Comparison of LSSI to other methods

5.3 Case Study: Beam Foundation

5.3.1 Model Description and Discretization in Sap2000

A concrete beam of width 1.00 m is considered, resting on an assumed elastic half space and loaded by four concentrated loads as shown in Figure 8. Two values of beam depth h and of the elasticity modulus E_s of the elastic soil are examined, namely, 0,80/0,30 m and

3.000/50.000 kPa, respectively. The concrete elastic modulus is assumed equal to 30.000 MPa. The respective modulus of subgrade reactions are $k= 2680 / 44620 \text{ kN/m}^3$.

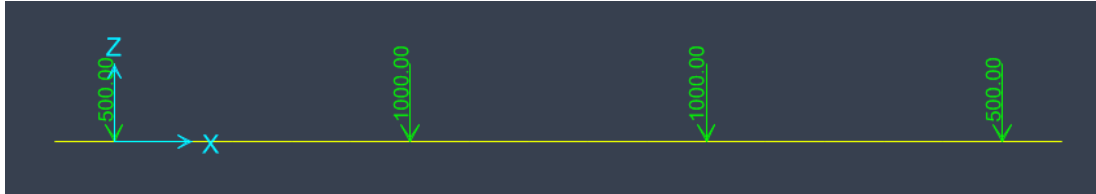
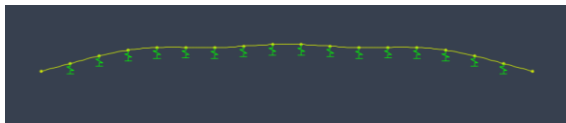


Figure 19 Foundation Beam

5.3.2 Output results

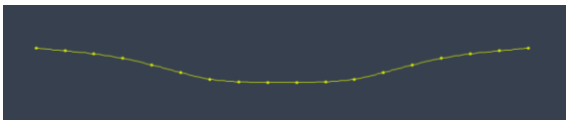
SETTLEMENTS



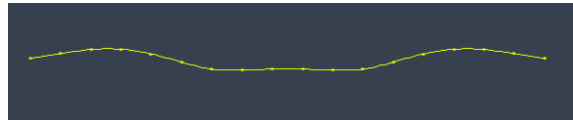
WINKLER_H80 cm_E3.000 kPa



WINKLER_H30 cm_E3.000 kPa



LSSI_H80 cm_E3.000 kPa



LSSI_H30 cm_E3.000 kPa



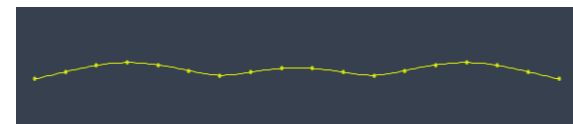
WINKLER_H80 cm_E50.000 kPa



WINKLER_H30 cm_E50.000 kPa



LSSI_H80 cm_E50.000 kPa



LSSI_H30 cm_E50.000 kPa

It can be noticed that only for a stiffer foundation on soil less deformable, the beam response with the LSSI procedure is close to the analysis considering the Winkler's method.

SOLLECITATION STATE

The bending moment diagrams obtained by the proposed method after dividing the beam into 15 equal finite elements are compared with those resulting from the Winkler's model, as seen in Figure 20, Figure 21.

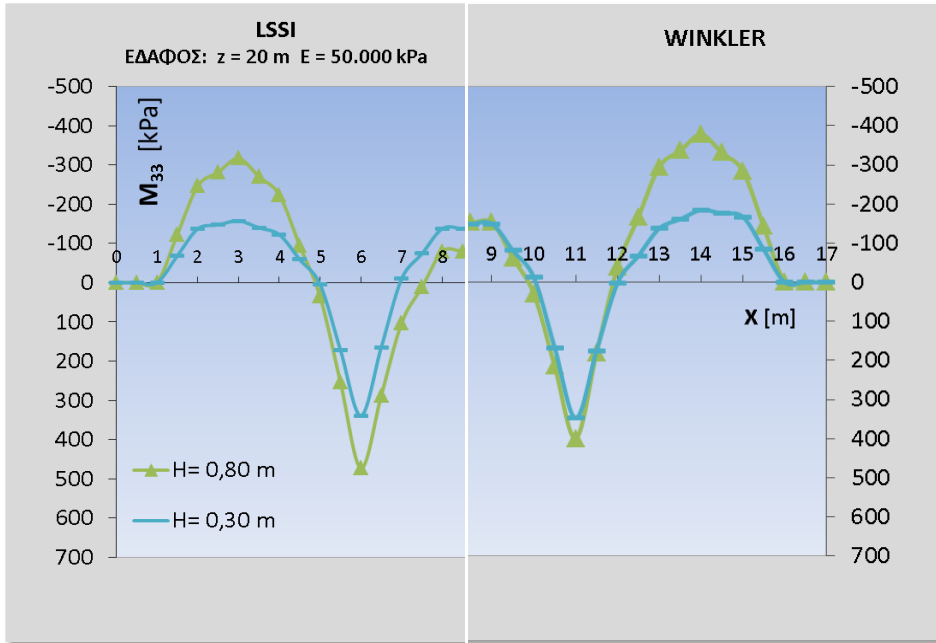


Figure 6 Bending response of foundation beam for E=3.000 kPa

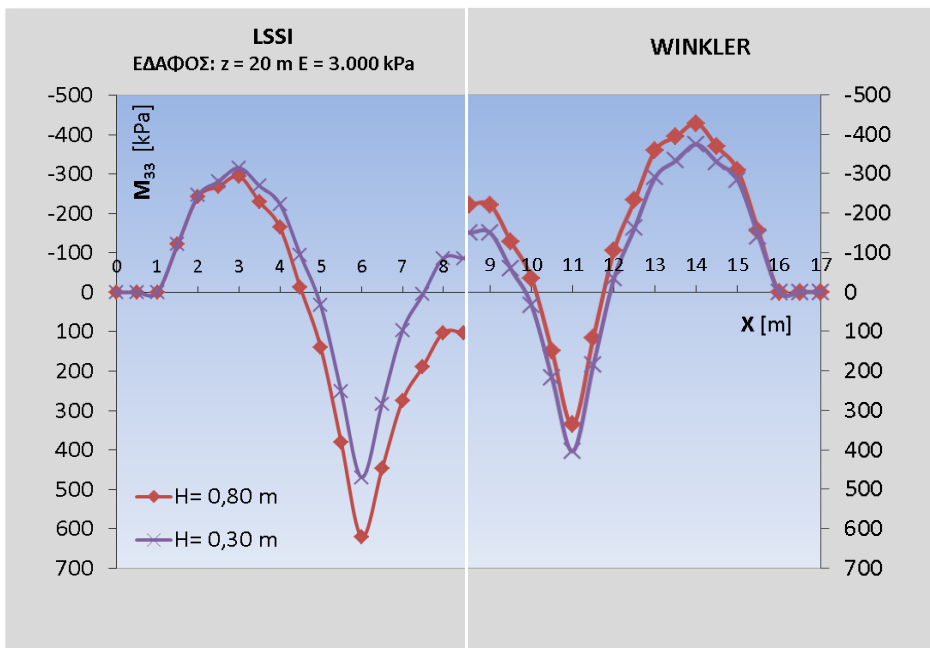


Figure 7 Bending response of foundation beam for E=50.000kPa

5.4 Other Significant Examples

5.4.1 Tunnel Frame

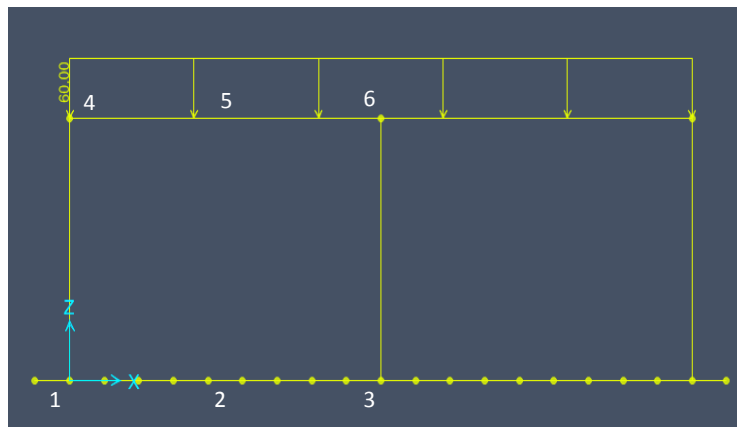


Figure 8 Tunnel frame

A band of unit length may be used for two-dimensional analysis of the concrete tunnel frame of Figure 8 which rests on a soil whose compression modulus E is variable, increasing linearly over a depth of 20.0 m. The respective frame thicknesses are $t = 40$ cm. The concrete elastic modulus is equal to $E = 30$ MPa. The foundation plate is divided into 18 equal finite segments, the nodes of which represent the contact nodes on which the fictitious structural model is simply supported. The support stiffness matrix is assembled through the repetitive analysis of the nineteen loading cases corresponding to the consecutive unit settlements of the model.

In order to evaluate the soil stiffness matrix over the contact nodes, the soil mass is discretized through a finite number (10) of layers with constant compression modulus. The Poisson's ratio is taken generally equal to 0.3.

The bending moments according to the elastic soil assumption are shown together with the ones based on the Winkler's method. A modulus of subgrade reaction k_s is equal to 8.020 kN/m^2 is considered.

The differences with the LSSI methodology are in this case concerning the sollecitation state are not very pronounced instead for settlements the Winkler's predictions are underestimated.

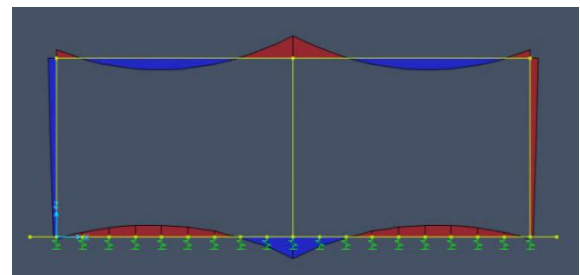
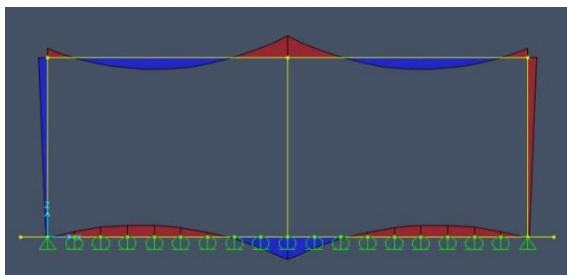
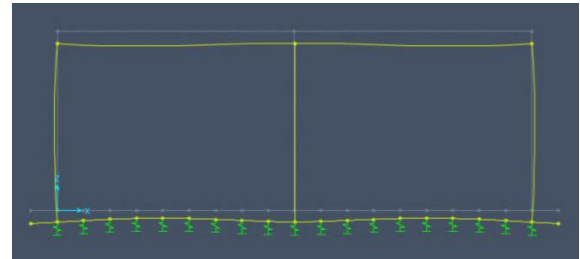
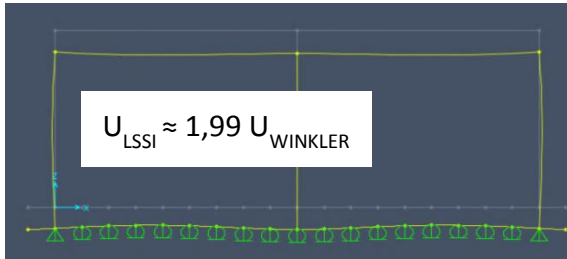


Figure 23 LSSI Analysis

Figure 24 Winkler Method Analysis

	LSSI	WINKLER
	Settlement [mm]	
s_1	-0.0125	-0.0069
s_2	-0.0107	-0.0048
s_3	-0.0132	-0.0068
	Moments [kNm]	
M_1	55.47	38.33
M_2	-278.51	-168.14
M_3	295.93	317.22
M_4	132.57	122.96
M_5	168.51	169.10
M_6	-331.58	-326.56

5.4.2 Structure on foundation with irregular plan

Multi-story concrete building with irregular plan with distributed vertical load in each floor of 50 kN/m. The concrete elastic modulus is equal to $E=30$ MPa. The foundation plate is divided into 18 equal finite segments

STRUCTURE WITH MAT FOUNDATION

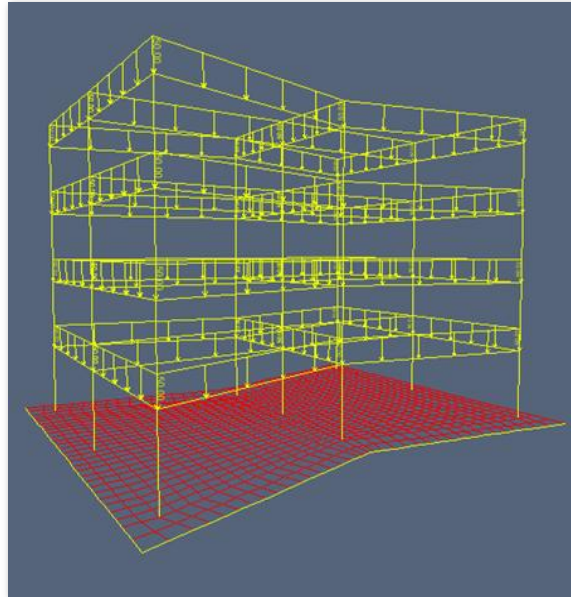


Figure 25 Multi storey structure

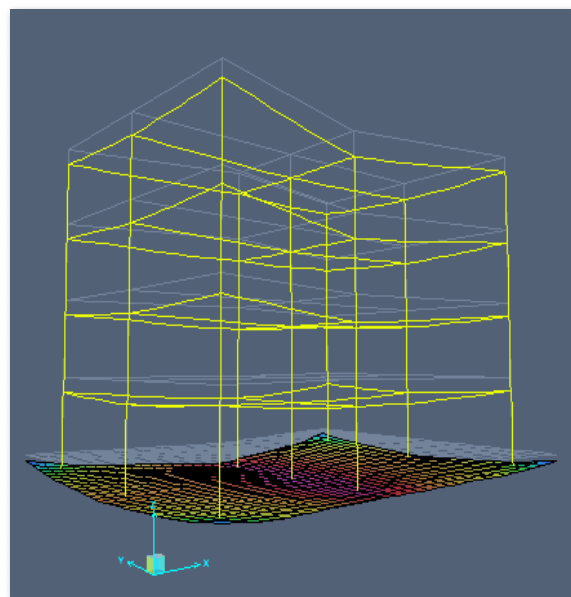


Figure 26 Deformed structure

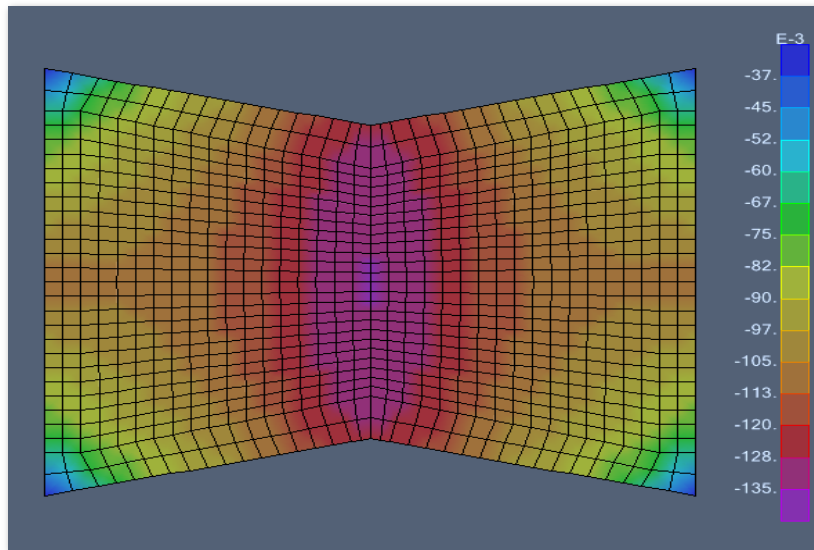


Figure 27 Foundation's settlements

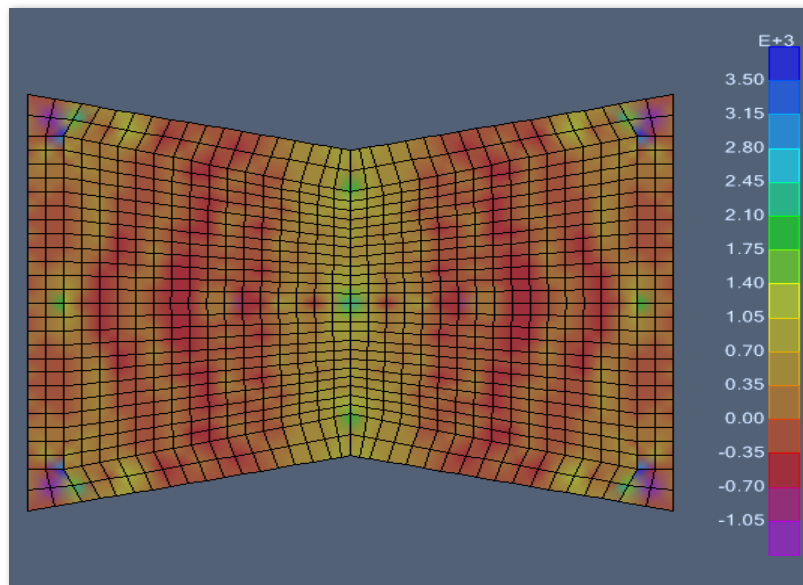


Figure 28 Foundation Moments, F_{11} [kNm/m]

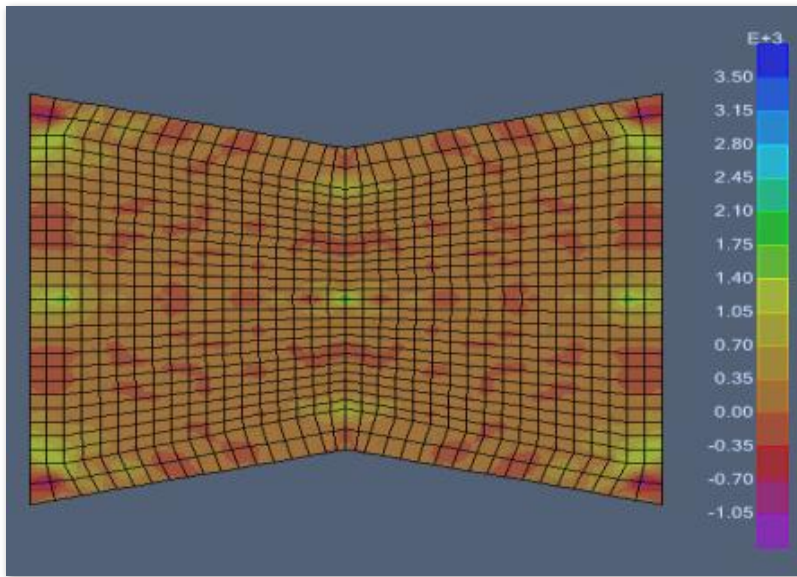
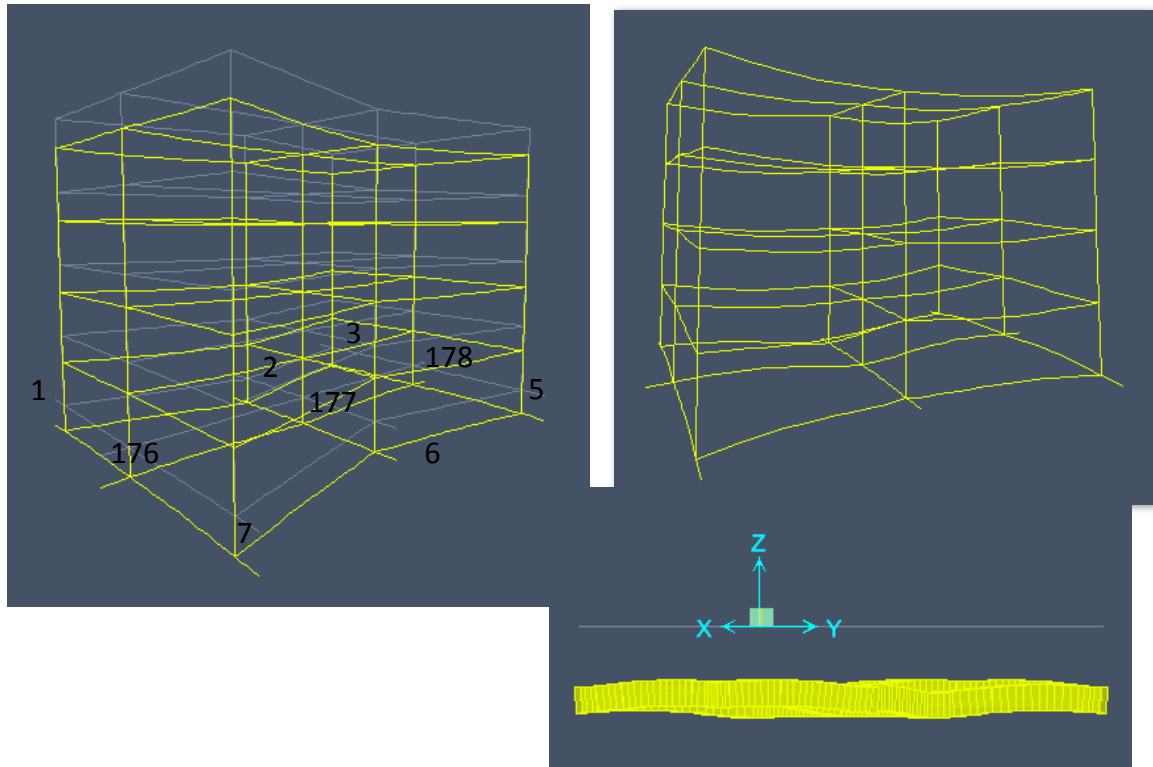


Figure 29 Foundation Moments, F22 [kNm/m]

BEAM FOUNDATION

The same building shown previously has been analyzed for beam foundation.



Joint	Settlement [m]
1	0.0565
2	0.0616
3	0.0565
178	0.0529
5	0.0565
6	0.0616
7	0.0565
176	0.0529
177	0.0600

Chapter 6

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 fulfill 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.
- After 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.

AKNOWLEDGMENTS

Advice and support from Prof. Konstantinos Spiliopoulos and Prof. Leonidas Stavridis are greatly appreciated.

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APPENDIX

Appendix A

OAPI FUNCTIONS

DEFINITION

The source code must begin with the following private subs that are important to call the Sap plugin otherwise the software will wait and will be hung!

```
Public Sub setParentPluginObject(ByRef inParentPluginObject As
cPlugin)

    ParentPluginObject = inParentPluginObject

End Sub

Public Sub setSapModel(ByRef inSapModel As
SAP2000v15.cSapModel, ByRef inISapPlugin As
SAP2000v15.cSapPlugin)

    SapModel = inSapModel
    ISapPlugin = inISapPlugin

End Sub

Private Sub FramesFromTextForm_Closing(ByVal sender As Object,
ByVal e As System.ComponentModel.CancelEventArgs) Handles
MyBase.Closing

    ' It is very important to call ISapPlugin.Finish(0)
when form closes, !!!
    ' otherwise, SAP2000 will wait and be hung
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

    ISapPlugin.Finish(0)

End Sub
```

Appendix B

SOFTWARE CAUTIONS

IN THIS APPENDIX ARE DESCRIBED IMPORTANT ANNOTATIONS AND REMARKS OBSERVED DURING THIS EFFORT IN ORDER TO PROVIDE GUIDELINES USEFUL TO COMPREHEND EITHER THE IMPLEMENTATION OF THE SOURCE CODE OR THE RIGHT EXECUTION OF THE LSSI PLUGIN TO ASSURE RELIABLE OUTPUT RESULTS.

SAP2000 VERSION

The source code of the LSSI plugin has been implemented for the latest so far available version of Sap2000, v15. In case of a newer version release, the instance of the SAP2000 object must be renamed first in the references created in the Microsoft Visual Studio software but also inside the source code where this object is initialized.

LSSI IMPLEMENTATION STEPS

Once Sap2000 has opened the SapModel file containing the structure appropriately discretized the user can import the LSSI form from the command *Tool* in the software's toolbar clicking *Add/Show Plug Ins...* and typing "LSSI" in both *Plug In Name* and *Menu Text* in order to load it.

To execute the LSSI analysis, the user must first define the numbers of layers including an extra layer representing the bed rock at the bottom of the soil profile and press OK. At this point the

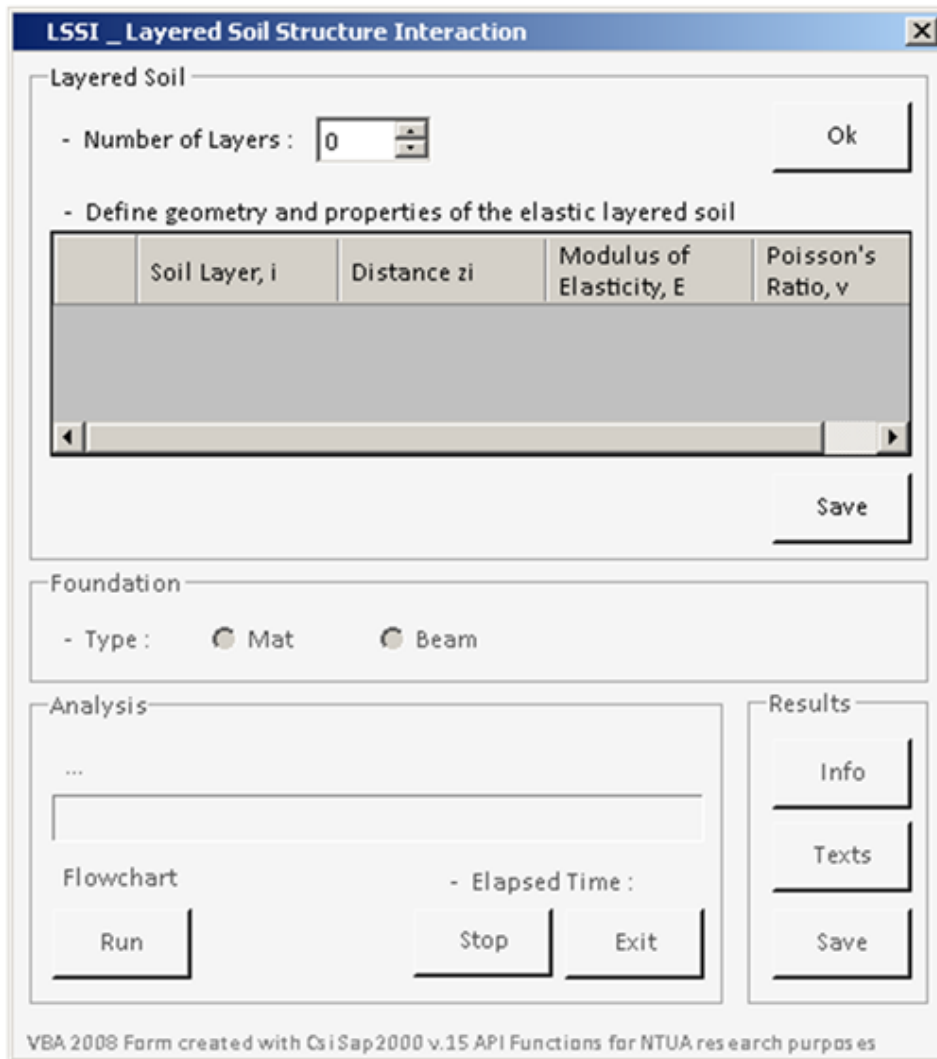


Figure 30 LSSI layout

data grid below is activated to insert geometric and elastic properties for each layer of the soil. Pressing the Save button the soil profile is being stored and the form asks for the foundation's type, whether our structure is supported on a mat slab foundation or on beams. By checking the appropriate radio button the user can finally *Run* the analysis following the procedure's execution from the progressbar. At the moment the analysis has arrived to its end the output groupbox is activated and the user can check about the analysis output data clicking the *Texts* button. *Info* provides information mainly about the various of elements defined, the soil imported and other general information.

GEOMETRY LIMITATIONS

This plugin supports only rectangular shapes of foundation, either regular or not; a circular shape would give incorrect results.

DISCRETIZATION ELEMENT'S TYPE AND SHAPE

The model is calibrated for area or frame finite elements with rectangular shape and four nodes. Thus the procedure's theory can also support solid element too, by easily expanding the source code using the appropriate OAPI functions.

UCS SYSTEM

The selection of Ucs system of the Sap2000 model must place the structure in positive coordinates for all x, y and z axis. The distance of the structure from the axis origin may give bugs during execution of the LSSI plugin due to double precision complications. To avoid this, the structure must be a few units distant from the origin, where with unit is intended the average length of the finite element used.

UNITS

The default units used during implementation of the source code are metric [kN, m, C] and must be set the same in the Sap2000 model.

INVERSION OF THE DEFORMABILITY MATRIX

In the LSSI procedure the stiffness matrix of the soil K_{SOIL} is obtained by inverting the associated deformability matrix. An inversion routine executed inside the source code of VB would delay considerably the end of process, in particular for foundations with a large number of contact nodes. To reduce the elapsed time of analysis, an inversion routine has been chosen to create an executable file using Fortran's programming. Once the deformability matrix of the soil is retrieved the CROUTROUTINE.exe is called from LSSI during analysis and in really few seconds provides the procedure the inverted matrix. For large structures, with many contact nodes, inversion may delay. The LSSI routine waits while the inversion's results are being retrieved with a message box "end of CROUTROUTINE".

Attention! The CROUTROUTINE.exe must be in the same directory of the generated output data texts of LSSI.

OUTPUT DATA DIRECTORY

The output data of LSSI analysis can be viewed either through Sap2000 or reading the various texts that report all the significant information of analysis. LSSI generates 13 .txt files in the directory C:\temp. The user has to make sure that the computer has this directory otherwise no output texts will create.

OUTPUT DATA FILES

The LSSI routine provides some output files, stored in the following directory: C:\temp

All these .txt files are being written at the end of the process except the TRIBUTARY file that writes data during the process, after storing them in arrays.

1. INFO

- File Name of the Sap Model Analyzed
- Units
- Soil Properties
- Defined Groups and Number of Sap Objects

2. LABEL

- Labels of the elements of the stiffness matrix [ISP x ISP]

3. TRIBUTARY

- Equivalent rectangle's dimensions of each tributary area
- Coordinates of the tributary areas displayed on the structure during the analysis process of LSSI.

4. REACT DEAD

- Reactions of the structure for the load case "DEAD" before and after the imposed settlements on the foundation's contact nodes, R_o and R_{sap} respectively.
- Reactions of the structure for the load case "SETTLEMENTS" that considers loads the imposed settlements at the contact nodes of the foundation representing the deformability of the soil supporting the sap model, R_{xa} .

This load case isn't involved in the LSSI analysis, is defined only to verify whether the final reactions given from the sap analysis were correctly retrieved.

$$R_o + R_{xa} = R_{sap}$$

5. SOIL_DEF_STIFF

- Soil deformability and stiffness matrix, Dsoil and Ksoil.
- Inversion test: $D_{soil} \cdot K_{soil} = I$

6. SUP_STIFF

- Support's stiffness matrix, Ksup

7. SSI_STIFF

- System's matrix , Kssi

8. SETTL

- Settlements of the foundation determined solving the linear problem:

9. LIN_SOL

- The settlements found must satisfy the equation: $(K_{soil} + K_{sup}) \cdot \Delta = R_o$