DETERMINING THE SUBGRADE MODULUS ACCORDING TO PHYSICAL PROPERTIES AND SHEAR STRENGTH PARAMETERS OF SOIL

MSc THESIS

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DETERMINING THE SUBGRADE MODULUS ACCORDING TO PHYSICAL PROPERTIES AND SHEAR STRENGTH PARAMETERS OF SOIL

YATAK KATSAYISININ ZEMİNİN FİZİKSEL ÖZELLİKLERİNE VE KAYMA MUKAVEMETİ PARAMETRELERİNE GÖRE BELİRLENMESİ

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To Founder of Turkish Republic

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- all audio-visual and written information and results have been presented according to the rules of scientific ethics,
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- I did not do any distortion in the data set
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19/ 06 / 2019

Emre AYGIN

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ÖZET

YATAK KATSAYISININ ZEMİNİN FİZİKSEL ÖZELLİKLERİNE VE KAYMA MUKAVEMETİ PARAMETRELERİNE GÖRE BELİRLENMESİ

EMRE AYGIN

Yüksek Lisans, İnşaat Mühendisliği Bölümü

Tez Danışmanı: Doç. Dr. Berna UNUTMAZ

Haziran 2019, 91 Sayfa

Bu tez çalışmasında, literatürdeki yaygın olarak kullanılan ancak kısıtlı sayıdaki yaklaşımlardan farklı olarak, yatak katsayısı zeminin ve temelin fiziksel ya da mekanik özelliklerini gösteren parametrelere (*Temel genişliği, uzunluğu, kalınlığı, Elastisite modülü, Poisson oranı vb.*), indeks özelliklerini gösteren parametrelere (*Sıkılık oranı, Özgül ağırlık, Birim hacim ağırlık vb.*) ve kayma mukavemeti parametrelerine (*İçsel sürtünme açısı, Kohezyon*) bağlı bir fonksiyon olarak belirlenmeye çalışılacaktır. Zeminlerin yatak katsayısının belirlenmesi özellikle temel yapılarının tasarlanması aşamasında inşaat mühendislerinin karşılaştığı en önemli konulardan bir tanesi haline gelmektedir. Üst yapı ve temelin tasarımlarda bir bütün olarak modellenerek analiz yapılması, çözümü karmaşık bir hale getirmekte ve tasarımcılara hem zaman hem de iş yükü açısından külfetler getirmektedir. Yukarıda sunulanlar doğrultusunda, elastik zemine oturan kiriş formundaki yapı elemanları, hem zemin parametrelerinin kontrol edilebildiği (PLAXIS) hem de edilemediği (SAP2000) nümerik programlarda ayrı ayrı modellenerek analiz edilmiştir. Bu analizlerden elde edilen sonuçlar karşılaştırılarak tutarlılık gözden geçirilmiş, sayısal sonuç olarak birbirine en çok yaklaşan modeller esas kabul edilmiştir.

Bu aşamadan sonra, zeminin özelliklerini etkileyen parametreler PLAXIS programı üzerinden sırasıyla değiştirilmiş, parametresi değiştirilen her bir modelin sonuçlarına karşılık gelecek şekilde SAP programı üzerinden yatak katsayısı (yay sabiti) değeri değiştirilerek yakın sonuçların yakalanması için çaba sarf edilmiştir. Her iki programın verdiği sonuç çıktılarında, zemine oturan kirişin oturma değerleri yakalanması gereken birincil parametre olarak seçilmiştir. Değişen zemin parametrelerine karşılık gelen yatak katsayısı değerleri tabloya aktarılmıştır. Zemin parametreleri kullanılarak, yatak katsayısı değerinin birimsel bütünlüğüne dikkat edilerek bir formül oluşturulmuş, bu formülden ortaya çıkan yatak katsayısı değerleri, analizlerde kullanılan yatak katsayısı değeri ile grafik üzerinden kıyaslanmıştır. “Maksimum Olabilirlik Tahmini” yöntemi kullanılarak minimum sapma ile elde edilen formül optimize edilmeye çalışılmıştır.

Anahtar Kelimeler: Zeminin kayma mukavemeti parametreleri, temelin geometrik özellikleri, yatak katsayısı

ABSTRACT

DETERMINING THE SUBGRADE MODULUS ACCORDING TO PHYSICAL PROPERTIES AND SHEAR STRENGTH PARAMETERS OF SOIL

EMRE AYGIN

Degree of Master of Science, Department of Civil Engineering

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In this thesis study; different from widely used but restricted number of existing approaches in the literature, subgrade reaction modulus is determined as a function of geometrical (width, thickness and length of foundation etc.), index (relative density, specific gravity, unit weight etc.), shear strength (cohesion, internal friction angle) or mechanical (Young's Modulus, Poisson's ratio etc.) properties of soil and foundation. Determining the subgrade reaction modulus has become one of the important issues at the phase of designing the foundation structures especially. Analyzing the superstructure and foundation structure as a whole complicates the solution and costs more time and effort. In accordance with aforementioned issues; structural members such as beams resting on elastic soil has been modeled and analyzed separately in numerical softwares such as SAP2000 and PLAXIS. Results obtained from these analyses, have been compared, consistency has been sought and models that converge to each other as numerical results have been assumed as elementary models.

A parametric study has been performed using different soil and foundation types in PLAXIS and the same models are tried to be modeled in SAP200 also. Among the outputs of PLAXIS and SAP, the maximum settlement value of beam resting on elastic soil has been chosen as the primary control parameter. Subgrade reaction modulus values corresponding to the different soil parameters have been transferred into tables. By taking into account the consistency of units, a formula has been proposed; subgrade reaction modulus values obtained from this formula has been compared with subgrade reaction modulus values that used in SAP analysis on a chart. By using “Maximum Likelihood Estimation” method, proposed formulation has been tried to be optimized.

Keywords : Shear strength parameters of soil, geometrical properties of foundation, subgrade reaction modulus

TEŞEKKÜR

Yüksek lisans eğitimim ve özellikle tez çalışmalarım boyunca, verdiği destek, sağladığı yönlendirme, yol göstericilik, bilgi ve değerli yardımlarından dolayı danışmanım sayın Doç. Dr. Berna UNUTMAZ'a sonsuz saygı ve teşekkürlerimi,

Yüksek lisans eğitimim boyunca sağladıkları değerli bilgiler ve kazandırdıkları bakış açısından dolayı değerli hocalarım sayın Doç. Dr. Mustafa Kerem KOÇKAR ve sayın Doç. Dr. M. Abdullah SANDIKKAYA'ya saygı ve teşekkürlerimi,

Tez jürimde bulunarak değerli görüş ve katkılarını sunan hocalarım sayın Doç. Dr. Zeynep GÜLERCE ve sayın Doç. Dr. Alper ALDEMİR'e saygı ve teşekkürlerimi

Yüksek lisans eğitimim ve tez çalışmalarım boyunca sağladıkları toleranstan ve destekten dolayı işyerim ARTI Mimarlık Mühendislik ve Müşavirlik ile değerli çalışma arkadaşlarıma teşekkürlerimi,

Hayatımın her anında, paha biçilmez destek, sevgi ve anlayışlarını esirgemeyen çok değerli aileme, yüksek lisans eğitimim boyunca gösterdikleri destek ve anlayışlarından dolayı değerli arkadaşlarıma sonsuz teşekkürlerimi ve sevgilerimi,

Sunarım…

Emre AYGIN
Haziran 2019, Ankara

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1. INTRODUCTION

Numerical modeling of soil-structure pair is one of the most troublesome issues in geotechnical engineering. Although soil does not show elastic behavior completely, by making an assumption in elastic limits, a solution has been tried to be put forth. The first approach is suggested by Winkler in 1867. According to Winkler's theory, the behavior of subgrade soil on which a beam or mat foundation is resting can be represented by springs. In this approach, the output is the contact pressure-settlement ratio and this ratio gives the spring constant called as "Subgrade Reaction Modulus". Many researchers have contributed to this approach after Winkler (1867). While some of them have dealt with this issue as a mathematical problem, others have conducted field tests and have evaluated the results.

In Turkey, Bowles' (1997) approach (a theory based on bearing capacity obtained from field test results) has been accepted in recent years. However, in cases where bearing capacity is not provided or not calculated, accurately determination of the subgrade reaction modulus becomes a issue.

The objective of this study is to determine the subgrade reaction modulus, independent from bearing capacity of soil (or equation) and providing practical and useful solution for designers. At the beginning, a beam whose dimensions are known has been modeled on (using both SAP and PLAXIS as numerical softwares) a generic soil profile. After a reference analysis, parametric study is conducted. A simplified equation to assess this spring constant has been proposed and conclusions have been evaluated.

1.1 Scope of Thesis

After this brief introduction, in Chapter 2, a comprehensive literature review is presented. Studies performed by many researchers have been submitted chronologically. This chapter contains equations, relations, figures, tables, results etc. from previous studies.

In Chapter 3, analytical models, encountered problems and some pre-results are presented. Until determining the correct model type, some problems have been encountered. By changing some geometrical and mechanical properties, more consistent results have been obtained.

In Chapter 4, final results have been submitted. By taking the approaches mentioned in literature review part into consideration, results have been evaluated. A simplified formulation for calculating subgrade modulus is proposed in this chapter.

In Chapter 5, summary and major conclusions of this study are presented.

2. LITERATURE REVIEW OF SUBGRADE MODULUS and WINKLER METHOD

2.1 Previous Studies

The analysis of the foundations placed on a flexible soil is based on the hypothesis that the reaction forces at each point of the foundation are proportional to the displacement at that point. Coefficient that describes the relation between displacement and forces is called as subgrade reaction modulus ‘k_0’ (or k_s some sources in literature). The basic method (Figure-2.1) about this approach was proposed by Winkler (1867). Winkler’s model is based on assumption that infinite number of springs represents the soil behavior. Springs only affect the vertical displacement of the structure. Defining the closely-spaced springs is significant for continuity of deformation behavior of foundation.

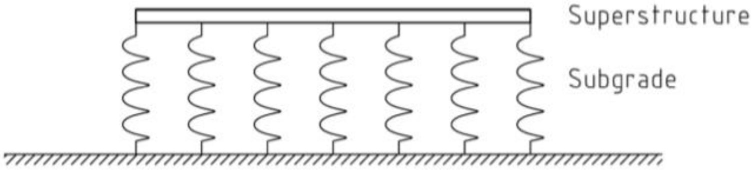
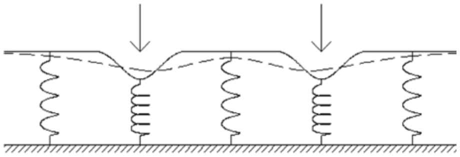


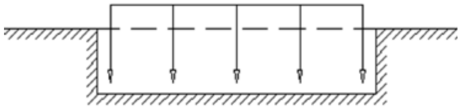
Figure-2. 1 Winker Model

Winkler’s single parameter model has been suggested for solution of railroad tracks firstly. It’s a very simple, familiar and the oldest method. However, it does not give consistent results for practical purposes. Main disadvantage of this method is that shear stresses cannot be transferred. Because of this discontinuity, springs near to the foundation member give unrealistic displacement values as can be seen in Figure-2.2a, 2.2b and 2.2c

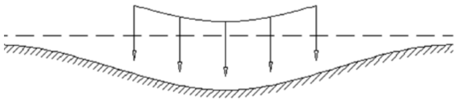


(a) Settlement Comparison of Winkler Model – In reality

Continuous line : Point loaded system according to the Winkler Model
Dashed line : Point loaded system observed in reality



(b) Distributed loaded system in Winker Model



(c) Distributed loaded system observed in reality

Figure-2. 2 Settlement behavior of Winkler Model & Real Case

Due to the fact that the shear stresses are not transferred, stiffness changes occur at the edges of the foundation. The distribution of contact pressure in accordance with elastic continuum theory is illustrated in Figure-2.3. In order to model the behavior that appears here, more rigidity can be defined to the springs at the edge zone.

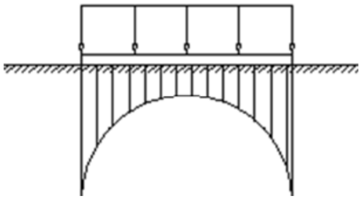


Figure-2. 3 Distribution of contact pressure according to the elastic continuum

In spite of this situation, a lot of designers prefer this method. Many researchers have dealt with solution of Winkler approach's discontinuity problem. Filonenko-

Borodich (1940), Hetenyi (1946), Pasternak (1954), Vlasov and Leontiev (1960) Kerr (1964) are some of them. Theories suggested by these researchers have two or more parameters. Multi-parameter models give more logical results than one-parameter model. It has been realized that if second parameter is ignored, mechanical behavior of Pasternak's model looks like the Winkler's model.

Filonenko-Borodich (1940) model has a flexible layer with tension force "T" (Pre-tensioned) on the surface of the springs of Winkler model (Figure-2.4). Therefore, the deformation of soil demonstrates the continuous behavior under load conditions (Figure-2.5a,b,c).

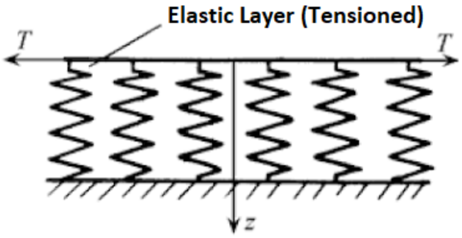
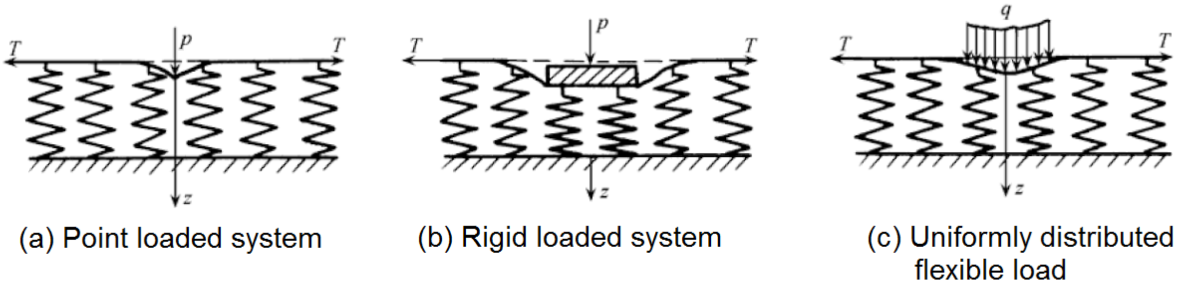


Figure-2. 4 Filonenko-Borodich Model (1940)



(a) Point loaded system

(b) Rigid loaded system

(c) Uniformly distributed flexible load

Figure-2. 5 Deformation characteristics under various load conditions

Hetenyi (1946) model has a flexible member (slab or beam) on the separated springs to provide the interaction between springs.

Pasternak (1954) model has assumed that there is a shear layer on the spring members (Figure-2.6). This shear layer can only enable shear deformation, however this layer is also incompressible, thereby, and the mutual shear actions of spring members are arisen.

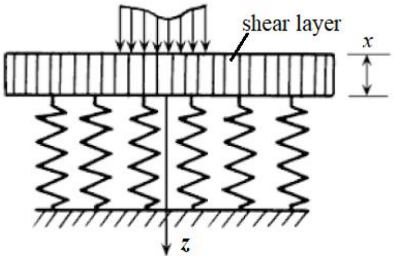


Figure-2. 6 Pasternak Subgrade Model

Three complicated sets of partial differential equations enable another approach for semi-infinite continuum behavior of soil. Therefore, simplifying assumptions about displacements and/or stresses are provided in order to enable a precise and easy solution of the remaining equations. These methods are called as “simplified-continuum models”. Vlasov and Leontiev (1966) adopted the simplified-continuum models based on variational principles and developed a two-parameter foundation model. In the model they developed, the foundation member was considered as an elastic layer and restrictions were applied by bringing the deformation in the foundation into a suitable mode shape. The two-parameter Vlasov model (Figure-2.7) enables the effect of the omitted shear strain energy in the soil and shear forces obtained from surrounding soil by including an arbitrary parameter ‘γ’ to symbolize the vertical distribution of the deformation in the subgrade. Vlasov and Leontiev didn’t suggest any relation or equation in order to calculate the parameter “γ”.

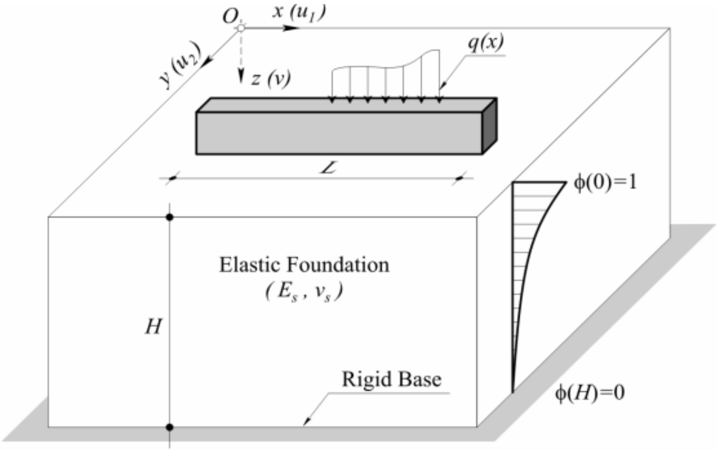


Figure-2. 7 Vlasov foundation model

The analytical solution under varied loading conditions has been developed for semi-infinite elastic continuum. The solution for point and distributed loading conditions has been proposed by 'Boussinesq' (1885). For derived approach, can be looked over to Timoshenko and Goodier (1970). On the other hand, subgrade model at lesser depths have not been defined sufficiently with semi-infinite space. By using 'simplified continuum', a solution with specific height (H) has been proposed by Reissner (1958). Elastic soil media is assumed as weightless in Reissner's equation.

Reissner's (1958) relation in elastic media that represents the soil properties can be seen in Equation-2.1;

$$q(x,y) - \frac{G_S * H^2}{12 * E_S} \nabla^2 q(x,y) = \frac{Es}{H} w(x,y) - \frac{G_S * H}{3} \nabla^2 w(x,y)$$

Equation-2. 1

Where; H: Height, E_S: Modulus of elasticity of Soil, G_S: Shear Modulus of Soil

Equation-2.1 explains the vertical force-settlement relationship for a simplified continuum. Kerr (1964) has developed a subgrade model with an equation on a similar form. Kerr's model comprises two spring layers and an incompressible shear layer in between that two layer as can be seen in Figure-2.8. Each spring layer is characterized with its own stiffness k_u, g_s and k_l (Horvath, 2002).

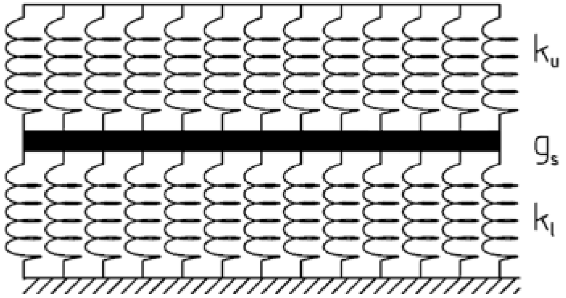


Figure-2. 8 Kerr's subgrade model

Kerr's differential equation for the vertical force-settlement relation;

$$q(x,y) - \frac{g_s}{k_u + k_l} \nabla^2 q(x,y) = \frac{k_u * k_l}{k_u + k_l} w(x,y) - \frac{g_s * k_u}{k_u + k_l} \nabla^2 w(x,y)$$

Equation-2. 2

By comparing the equations Reissner and Kerr, the relations between the parameters are given in Equation 2.3a,b,c ;

$$k_u = \frac{4 * E_s}{H} \qquad k_l = \frac{4 * E_s}{3 * H} \qquad g_s = \frac{4 * G_s * H}{9}$$

(a) (b) (c)

Equation-2. 3

According to Horvath (2002), Kerr's model is not applicable to much commercial software. Kerr's shear layer is structurally equivalent to a deformed, pre-tensioned membrane. Horvath has been suggested a modified Kerr's model whose name is Modified Kerr-Reissner (MK-R). In the MK-R model, main approach is the same as in Kerr's model, but the pre-tensioned membrane is used instead of the shear layer as might be seen in Figure-2.9 (Horvath, 2002);

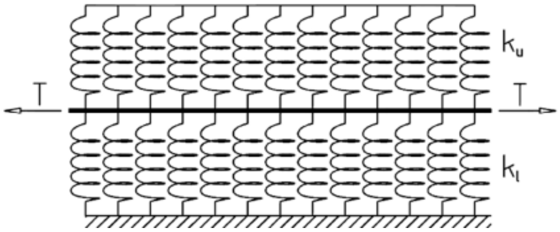


Figure-2. 9 MK-R model

Mathematical expression of MK-R model is given in Equation-2.4;

$$q(x,y) - \frac{T}{k_u + k_l} \nabla^2 q(x,y) = \frac{k_u * k_l}{k_u + k_l} w(x,y) - \frac{T * k_u}{k_u + k_l} \nabla^2 w(x,y)$$

Equation-2. 4

Spring stiffnesses are (k_l and k_u) same as the Equation-2.3. Pre-tension force ‘T’ in the Equation-2.4 is calculated as in Equation-2.5;

$$T = \frac{4 * G_s * H}{9}$$

Equation-2. 5

It should be noted that the analysis should include the secondary effects; otherwise the pre-tensioned membrane will not work appropriately.

After a general review of the Winkler's theory and the spring assigning approach, ‘Subgrade Reaction Modulus’ is the spring constant represents the elasticity of the soil, can be expressed in the Equation-2.6 as general;

$$\frac{p}{w} = \text{Constant} = k$$

Equation-2. 6

Biot has evaluated the problem of determining the subgrade reaction modulus as an analytical approach. Biot’s (1937) theory is based on the hypothesis which assumes the beam (Figure-2.10) resting on top of a wall infinitely high and long can be considered as two-dimensional foundation.

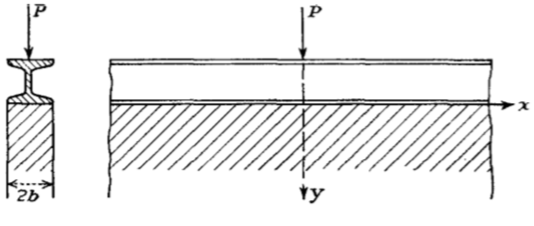


Figure-2. 10 Beam resting on infinite wall, in Biot’s approach

After that first assumption, Biot has put forth the load, stress, fundamental length of beam and deflection (displacement) equations as can be seen in Equation-2.7a,b and Equation-2.8a,b

$$Q = Q_0 \cos\lambda x \qquad \frac{\partial^4 F}{\partial x^4} + 2\frac{\partial^4 F}{\partial x^2 \partial y^2} + \frac{\partial^4 F}{\partial y^4} = 0$$

(a) Sinusoidal load per unit length (b) Stress Components in the Foundation

Equation-2. 7 Biot's load and stress relations

$$a = [\frac{E_b I}{E_b}]^{½} \qquad E_b I \frac{d^4 w}{dx^4} = P - Q$$

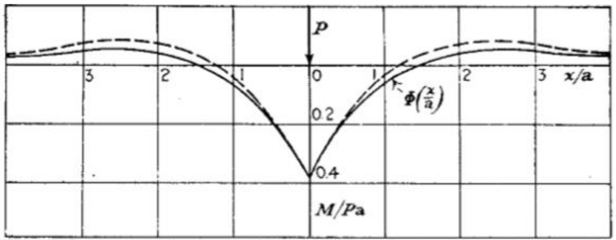
(a) Fundamental Length (b) Deflection

Equation-2. 8 Biot's length and deflection relations

By defining the boundary conditions and taking some integrals, Biot has obtained maximum bending moment (Equation-2.9 and 2.11) and subgrade reaction modulus (Equation-2.10 and 2.12) value for both two-dimensional and three-dimensional conditions.

$$M(x) = Pa\,\frac{1}{\pi}\int_0^\infty \frac{\alpha\cos(\alpha\frac{x}{a})}{\alpha^3+1}\,d\alpha.$$

Equation-2. 9 Bending moment according to the two dimensional calculations



(The solid curve was drawn by the exact theory for two-dimensional foundations. The dashed curve was drawn by the elementary theory with a value of the modulus *k* adjusted so that the maximum bending moment has the correct value.)

Figure-2. 11 Bending moment curves according to the Biot's relations

$$k = 0.710 \left[\frac{Eb^4}{E_b I} \right]^{½} E$$

Equation-2. 10 Two-dimensional Subgrade reaction modulus formula

$$M(x) = \frac{P}{\pi} \int_0^\infty \frac{\lambda .\cos\lambda x .d\lambda}{\lambda^3 + \frac{1}{C(1\text{-}\nu^2)} \frac{E}{Eb} \frac{b}{I} \Psi(\beta)}$$

Equation-2. 11 Bending moment according to the three dimensional calculations

In three-dimensional conditions, Poisson’s ratio has also been included into the calculations. It has been observed that in the Biot’s theory, equations for three-dimensional conditions give more accurate results than equations for two-dimensional conditions. Finally, Biot (1937) has proposed the equation for determining the subgrade reaction modulus according to his theory as presented in Equation-2.12;

$$k_s = \frac{0.95\, E_s}{B(1\text{-}v^2)} \left[\frac{B^4\, E_s}{(1\text{-}v_s^2)EI} \right]^{0.108}$$

Equation-2. 12 Three-dimensional Subgrade reaction modulus formula

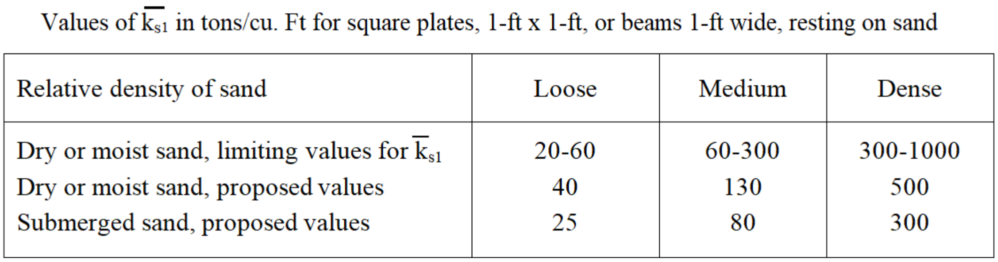
Wherein;

E_s : Modulus of elasticity of Soil
E : Modulus of elasticity of Foundation
I : Moment of Inertia of Foundation (around bending axis)
B : Width of Foundation
v_s : Poisson Ratio of Soil

Studies of Terzaghi (1955) determine the subgrade reaction modulus based on the field test results. A plate loading test has been conducted on site for plates whose dimensions are specific (1x1-ft square plate). Then, results are utilized for the purpose of obtaining the subgrade reaction modulus for any type of foundation.

Terzaghi suggested the unit values 'k_{s1}' for subgrade reaction modulus. For cohesionless soils, k_{s1} values can be examined in Table-2.1;

Table-2. 1 Suggested Unit Subgrade Reaction Modulus Values 'k_{s1}' for sands



Values of $\overline{k}_{s1}$ in tons/cu. Ft for square plates, 1-ft x 1-ft, or beams 1-ft wide, resting on sand

Relative density of sand	Loose	Medium	Dense
Dry or moist sand, limiting values for $\overline{k}_{s1}$	20-60	60-300	300-1000
Dry or moist sand, proposed values	40	130	500
Submerged sand, proposed values	25	80	300

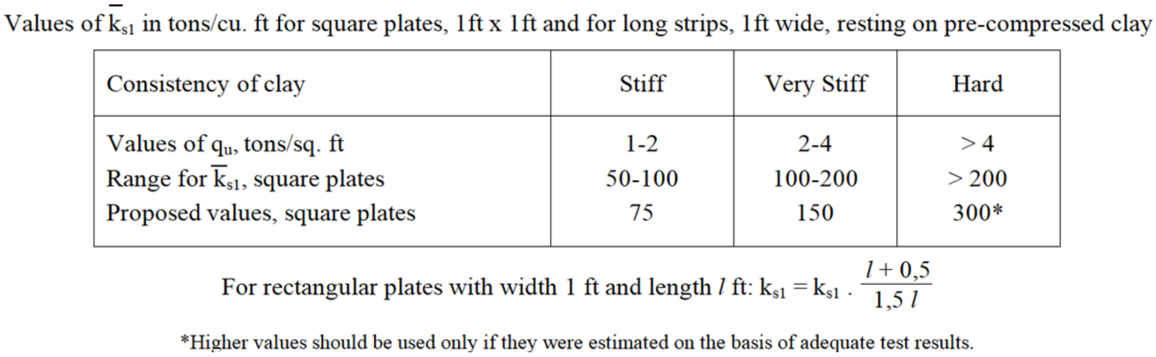
If necessary, density-category of sand can be determined by conducting a SPT or another convenient test. It has been realized that the value k_{s1} for a beam whose width is 1ft approximately equal to the k_{s1} value for a square plate whose width is 1ft. After determining the k_{s1} value, required k_s value for a beam with 'B' ft. width can be calculated by means of Equation-2.13;

$$k_s = \overline{k}_{s1} \left(\frac{B+1}{2\,B} \right)^2$$

Equation-2. 13 Subgrade reaction modulus for foundations resting on sand

If the soil is composed of heavily pre-compressed clay, the value of k_{s1} increases with proportionally to the unconfined compressive strength of the clay 'q_u'. For the pre-compressed clays, Terzaghi (1955) presented the k_{s1} values in the Table-2.2;

Table-2. 2 Suggested Unit Subgrade Reaction Modulus Values 'k_{s1}' for clays



Values of $\overline{k}_{s1}$ in tons/cu. ft for square plates, 1ft x 1ft and for long strips, 1ft wide, resting on pre-compressed clay

Consistency of clay	Stiff	Very Stiff	Hard
Values of q_u, tons/sq. ft	1-2	2-4	> 4
Range for $\overline{k}_{s1}$, square plates	50-100	100-200	> 200
Proposed values, square plates	75	150	300*

For rectangular plates with width 1 ft and length l ft: $k_{s1} = \overline{k}_{s1} \cdot \frac{l + 0{,}5}{1{,}5\,l}$

*Higher values should be used only if they were estimated on the basis of adequate test results.

Recommended formula by Terzaghi (1955) in order to determine the 'k_s' value for pre-compressed (considered as stiff) clays can be seen in Equation-2.14;

$$k_s = \overline{k}_{s1} \left(\frac{1}{B} \right)^2$$

Equation-2. 14 Subgrade reaction modulus for foundations resting on stiff clay

Terzaghi (1955) has adverted also horizontal subgrade reaction modulus for vertical piles, piers, sheet piles, anchored bulkheads and flexible diaphragms on his study. But in this paper, vertical subgrade reaction modulus has been examined only.

Vesic's (1961) studies on Subgrade Reaction Modulus are based on studies of Biot (1937). Vesic (1961) has obtained various conclusions by conducting detailed studies on analytical expressions such as integrals. Vesic also stated "*the Winkler's approach is useful for beams resting on semi-infinite elastic soil. Any problem of bending of an infinite beam can be solved with a conventional analysis by using subgrade reaction modulus* k_s*.*" Vesic has suggested the Equation-2.15 for the Subgrade reaction Modulus;

$$k_s = \frac{0.65\ E_s}{B\ (1 - v_s^2)} \sqrt[12]{\frac{E_s B^4}{EI}}$$

Equation-2. 15 Vesic's equation for Subgrade Reaction Modulus

In his "Foundation Analysis and Design", Bowles (1997) described the subgrade reaction modulus as in Equation-2.16;

$$k_s = \frac{\Delta\sigma}{\Delta\delta}$$

Equation-2. 16 Main Equation of Subgrade Reaction Modulus

$\Delta\sigma$ and $\Delta\delta$ corresponds increment of contact pressure and settlement changes respectively. Subgrade reaction modulus can be seen at Figure-2.12 (Hooke’s stress-strain relation chart).

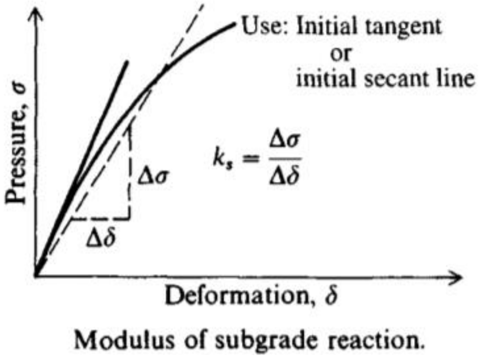


Figure-2. 12 Hooke’s Stress-Strain relation

The bold curve in the graphic, can be obtained from plate load test outputs. K_s is defined as slope of secant line that cuts the curve two points: $\delta=0$ and $\delta=0.0254$m (or 25mm). It is laborious to obtain good results from plate load test except for small plates. Since larger plates (e.g. 450, 600 or 700 mm diameter) tend to be less rigid than smaller ones, steady settlement measurement is difficult to obtain in those. Using stacked plates (can be seen in Figure-2.13) makes all the system more rigid so that obtaining the σ – δ plot becomes easier.

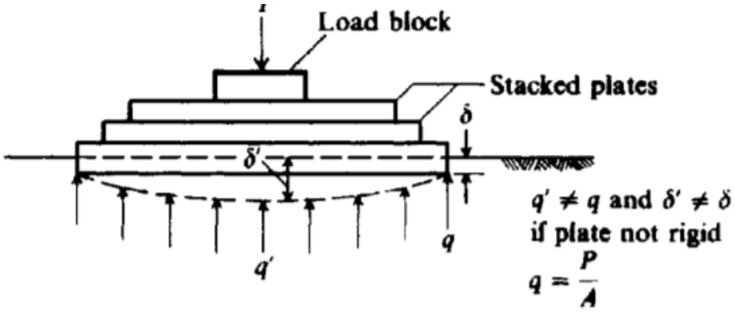


Figure-2. 13 Plate load test illustration

Bowles (1997) stated that when the determining k_s, used bending moments and computed soil pressures are not very sensitive. Since the mat (or footing etc) rigidity is 10 or more times great than soil stiffness generally. By considering this situation, Bowles has suggested Equation-2.17a, b;

For SI unit system : $k_s = 40.(FS).q_a$ (kN/m^3) (a)
For Fps unit system : $k_s = 12.(FS).q_a$ (k/ft^3) (b)

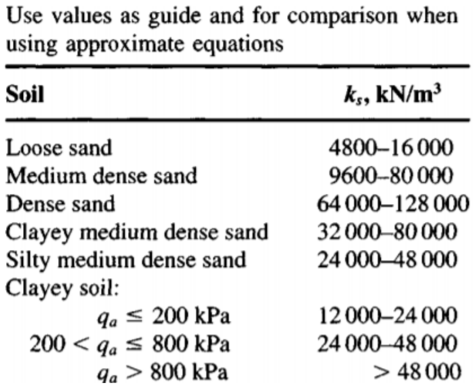
Wherein, FS=Factor of Safety, q_a=Allowable Bearing capacity

Equation-2. 17 Bowles' equation for Subgrade Reaction Modulus

This equation comes from $q_a = q_u / FS$ and settlement at the ultimate soil pressure is $\Delta H=0.0254m$ (or 1in) and $k_s = q_u / \Delta H$. If ΔH would be assumed as 6,12, 20mm, the factor 40 (12 for Fps units) adjusts as 160, 83, 50 respectively (48, 24, 16 for Fps units).

Bowles has proposed Table-2.3 for different types of soil. It should be noted that if calculated value is 2-3 times greater than the values at Table-2.3, calculations should be reviewed for a potential mistake. If there is no mistake in the calculations, decide which value to use. Designer shouldn't use the average of the values given in Table-2.3.

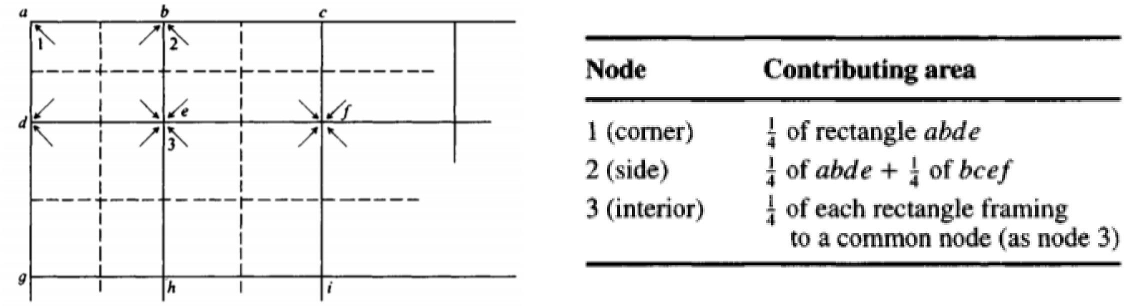
Table-2. 3 Subgrade Reaction modulus 'k_s' for sandy soils



Use values as guide and for comparison when using approximate equations

Soil	k_s, kN/m³
Loose sand	4800–16 000
Medium dense sand	9600–80 000
Dense sand	64 000–128 000
Clayey medium dense sand	32 000–80 000
Silty medium dense sand	24 000–48 000
Clayey soil:	
$q_a \leq 200$ kPa	12 000–24 000
$200 < q_a \leq 800$ kPa	24 000–48 000
$q_a > 800$ kPa	> 48 000

Bowles has also submitted a solution method that uses the subgrade reaction modulus. Mat foundation area is divided into smaller areas that are called "mesh". Each intersection is point called as 'node' and springs are placed at nodes. In this system, springs are independent of each other and uncoupled. Uncoupling means, the deflection of any spring is not affected by the adjacent one. Particular part of each divided area (mesh) contributes to the each spring which can be seen in Figure 2.14a, b.



Node	Contributing area
1 (corner)	$\frac{1}{4}$ of rectangle *abde*
2 (side)	$\frac{1}{4}$ of *abde* + $\frac{1}{4}$ of *bcef*
3 (interior)	$\frac{1}{4}$ of each rectangle framing to a common node (as node 3)

(a) (b)

Figure-2. 14 Spring coupling criteria

If divided area is a triangle, one-third of the triangle area should be used at any corner node as can be seen in Figure 2.15;

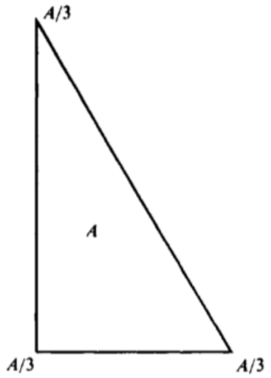


Figure-2. 15 Triangle mesh

Some designers prefer using Finite Element Method rather than Winkler foundation (springs) due to the fact that the springs are uncoupled. However, there is not enough numerical examples that shows that Finite Element Method provides better solutions. According to Bowles, subgrade reaction modulus method is less time consuming and easier. Moreover, spring coupling can be implied as follows;

1. "*Edge springs can be defined as double-timed only under these conditions;*"
   a. "The foundation is uniformly loaded"
   b. "There is only one at most two columns loads on foundation."
   c. "The computed node soil pressures 'q' are in the range of mat load Σ(P/Am)." 'Am : Area of the Mat'. If there are large differences, do not double the edge springs."

2. "*We can zone the mat area using softer springs in the innermost zone and transitioning to the outer edge. Use 1.5 to 2x$k_{s,interior}$ for the edge nodes.*

3. *"You shouldn't both double the edge springs and zone the mat area for the same program execution. Use either one or the other, or simply use a constant k_s beneath the entire foundation. It is recommended that method as follows:"*
   a. "*Make a trial run and obtain the node pressures*"
   b. "*Use these node pressures and compute the pressure increase at adjacent nodes.*"

Daloğlu and Vallabhan (2000) stated that when soil is stratified with different thicknesses, even if material properties maintain the same, an equivalent k_s value that depends on layer thickness should be used. It should be noted that thickness and k_s have inverse ratio. Thus, it has been emphasized that different material and dimensional properties of soil cause different k_s values. These researchers have utilized non-dimensional parameters for the purpose of determining the value of subgrade reaction modulus for use in the Winkler model for the analysis of foundation members exposed to concentrated and uniformly distributed loads. To provide the compatibility, Poisson's ratio has been used as a constant value, i.e.: ν=0.25. Researchers have not expected that this situation affect the results dramatically. Graphics that are related with this process are presented in the following sections.

Daloğlu and Vallabhan (1997, 1999) have used their finite element model for evaluation of slabs resting on an elastic soil. In this approach, in order to modeling the soil, two parameters are necessary. For providing consistency, a number of iterations should be performed. This method is based on assumption that soil is a finite media lying on hard, rigid material. The determining differential equations have been non-dimensionalized as below. Supposing the slab has a constant thickness at every point, the characteristic length 'r' is defined as in Equation-2.18:

$$r = \sqrt[4]{\frac{D\,H}{E_s}}$$

Equation-2. 18 Characteristic length of slab 'r'

Where; D: Flexural rigidity of slab, H: Depth of the soil layer, E_S: Modulus of elasticity of Soil

The coordinate axes and the lateral deflection '*w*' have been non-dimensionalized as; "***X=x/r, Y=y/r, Z=z/r*** and ***W=w/r***". By using non-dimensional parameters, in Vlasov model, the field equation for foundation resting on elastic sub-soil is described in Equation-2.19;

$$\nabla^4 W - 2T_n \nabla^2 W + K_{nv} W = Q_n$$

Equation-2. 19 Field equation for foundation resting on elastic soil (Vlasov)

Wherein; $k_{nv} = \frac{kr^4}{D}$; $2T_n = \frac{2tr^2}{D}$; $Q_n = \frac{qr^3}{D}$;

K_{nv} : Non-dimensional subgrade reaction modulus (for the Vlasov model)

T_n : Non-dimensional shear stiffness (for the Vlasov model)

∇^4 : Biharmonic operator

∇^2 : Laplace operator

Q_n : Distributed pressure on the slab

t : soil-shear parameter in dimension

q : Distributed load

Graphics from studies of Daloğlu and Vallabhan (2000) is as follows;

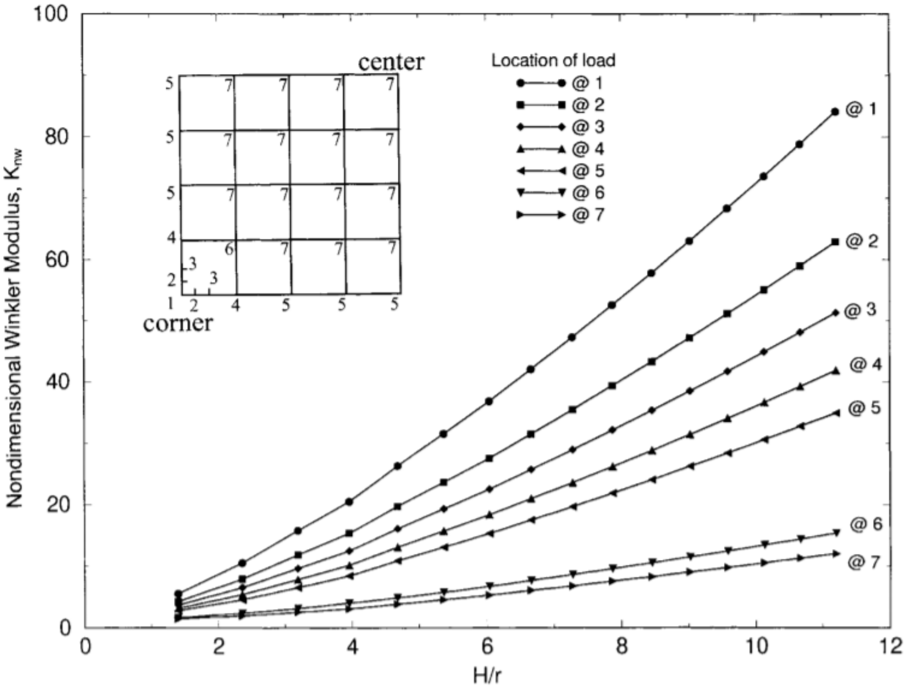
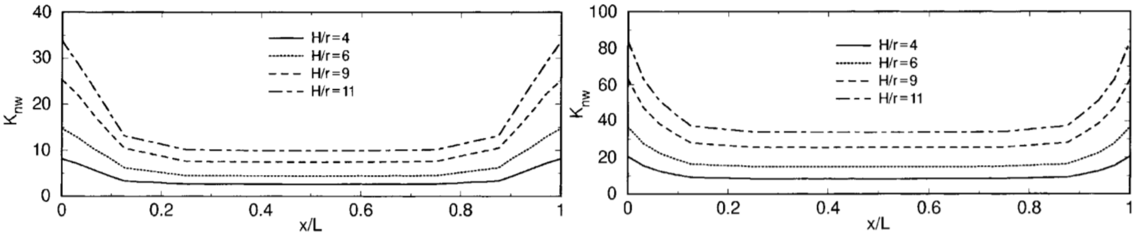
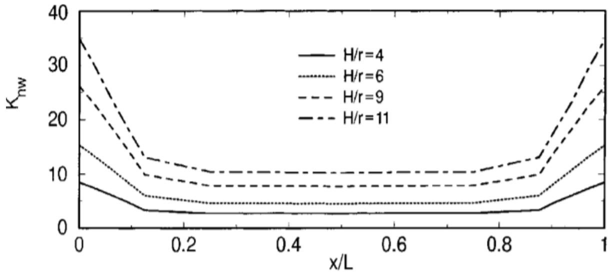


Figure-2. 16 Non-dimensional subgrade reaction modulus for Winkler model

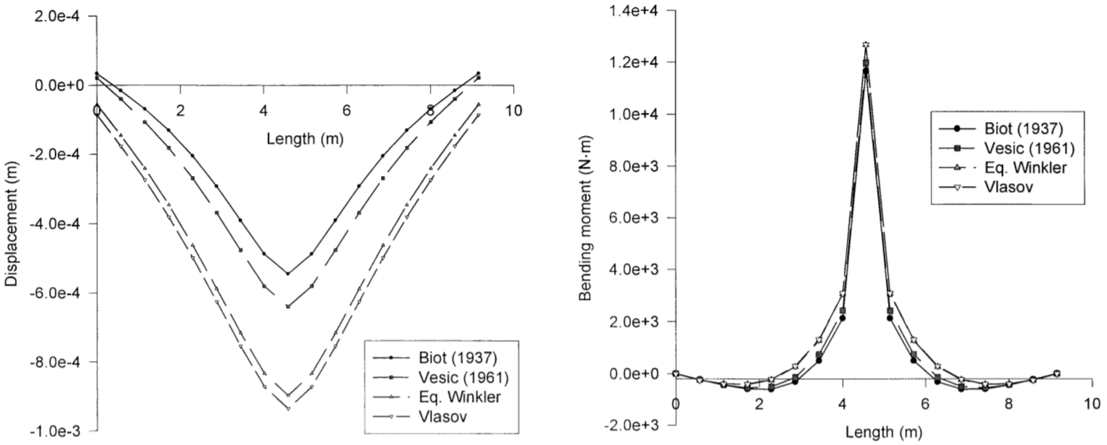


(a) Centerline of foundation (b) Edge of foundation



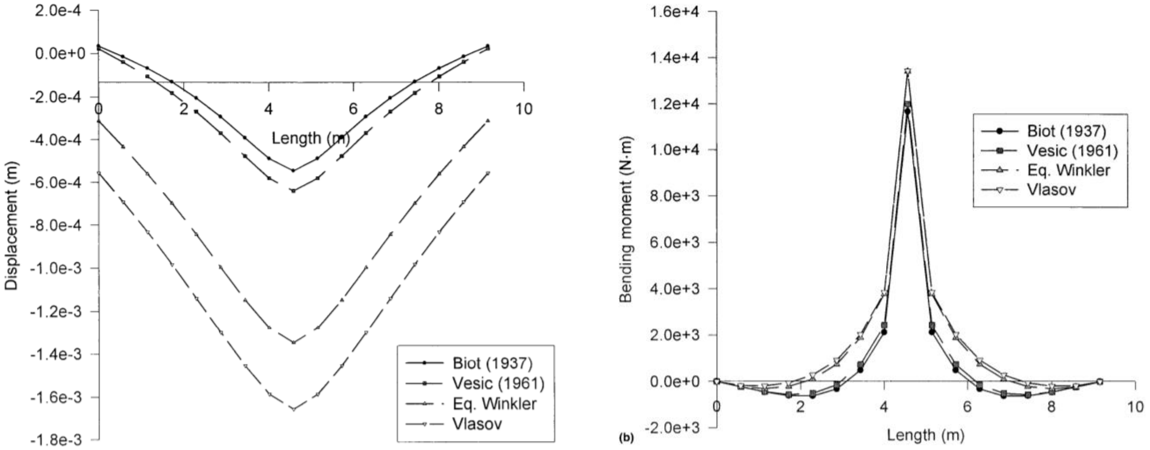
(c) Quarter length of foundation

Figure-2. 17 Variation of non-dimensional subgrade reaction modulus ‘K_{nw}’



(a) Displacement (b) Bending Moment

Figure-2. 18 Comparison of results throughout centerline of the foundation for concentrated load at center zone (.H=1.524m.)



(.a.) Settlement (.b.) Bending Moment

Figure-2. 19 Comparison of results throughout centerline of the foundation for concentrated load at center (H=6.098m)

By using the non-dimensional parameter ‘K_{nv}’ obtained from the Vlasov model, it has been mentioned about the non-dimensional K_{nw} for the Winkler model in following paragraphs. After conducting the numerical analysis of the foundation by using Vlasov model, K_{nv} value and maximum settlement at the center under the load has been calculated. By using this K_{nv}, same slab has been analyzed at the Winkler model and corresponding value for the maximum settlement at the center is calculated. An equivalent subgrade reaction modulus value for the Winkler model has been calculated by utilizing the proportion between the maximum settlement values from the two models (Foundation analysis in Vlasov and Winkler model). Foundation has been analyzed in the Winkler model by using the new subgrade reaction modulus until the maximum displacement differences obtained from the two models reach a negligible level. 'K_{nw} – H/r' variation plot is given in Figure-2.16, variation of K_{nw} along the slab is given in Figure-2.17.

To summarize;

i) The subgrade reaction modulus, 'r' (Equation-2.18) should be calculated at first.

ii) Then, K_{nw} values to be used in calculation of subgrade reaction modulus should be read in Figure-2.16 by using the H/r ratio.

iii) Finally, subgrade reaction modulus can be calculated with Equation-2.20;

$$k = \frac{K_{nw}\, D}{r^4}$$

Equation-2. 20 Subgrade Reaction Modulus proposed by Daloğlu & Vallabhan (2000)

Using the equation proposed by Daloğlu and Vallabhan (2000) provides less uncertainty to the engineer for defining the subgrade reaction modulus. Moreover, subgrade reaction modulus can be defined depending on the properties and the geometry of the foundation and that of the soil by using this method. Conclusions reached by authors (Daloğlu & Vallabhan, 2000) can be summarized as follows;

- "*If one uses a constant value of the modulus of subgrade reaction for a uniformly distributed load, the displacements are uniform and there are no bending moments and shear forces in the slab. In order to get realistic results, higher values of k have to be used closer to the edges of the slab.*"
- "*The value of k depends on the depth of the soil layer.*"
- "*Non-dimensional values of k are provided for different non-dimensional depths of the soil layer, from which equivalent values of k can be easily computed.*"

Dutta and Roy (2002) have focused on soil, foundation and structure interaction and examined the approaches about these issues rather than suggesting a method for determining the subgrade reaction modulus. They have mentioned that the reaction of any structural system which includes more than one member is inter-dependent all the time. For example, suppose a beam supported by three columns that have single footing as can be seen in Figure-2.20. Since higher load concentration on the central column, soil below it tends to settle more. However, edge columns tend to settle more as the central column by means of load transfer provided by beam. Therefore, values of force quantities or settlements etc. should be obtained from interactive analysis of the soil-structure foundation system. This example emphasizes that importance of soil-structure interaction.

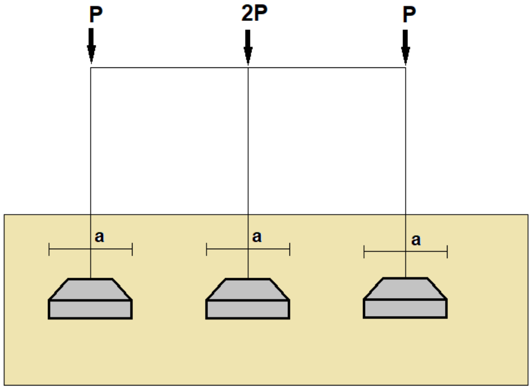


Figure-2. 20 Simple frame consisting with a beam and three columns

According to the authors (Dutta & Roy), studies show that two-dimensional analyses have resulted in significant deviations in comparison with three-dimensional analyses with regard to interaction effect. Another issue is the assumption that the structures are fixed at their footing. However, elasticity of footings (supports) affects the overall rigidity of structures and natural period of the system will increase. Hence, the seismic response of system changes considerably with natural period (spectral acceleration). It can be seen that if the soil-structure-foundation interaction analysis is not performed, a completely misleading behavior can be obtained. It is generally encountered that the modeling of the superstructure and foundation are quite simple than that of the soil medium underneath.

Contact pressure distribution at the foundation-soil interface is a significant parameter. The change of this parameter depends on the foundation manner (rigid or flexible) and nature of soil media (clay or sand). Aim of the foundation design is to transfer the loads of the structure to the soil, therefore, the optimal foundation modeling is that wherein the distribution of contact pressure is simulated in a more realistic manner. Conclusions reached by Dutta & Roy (2002) have been summarized as following;

- "*To accurately estimate the design force quantities, the effect of soil–structure interaction is needed to be considered under the influence of both static and dynamic loading.*"
- "*Winkler hypothesis, despite its obvious limitations, yields reasonable performance and it is very easy to exercise.*"
- "*Modeling the system through discretization into a number of elements and assembling the same using the concept of finite element method has proved to be a very useful method, which should be employed for studying the effect of soil–structure interaction with rigor.*"
- "*The effect of soil–structure interaction on dynamic behavior of structure may conveniently be analyzed using lumped parameter approach.*"

2.2 Concluding Remarks

In this chapter, Winkler approach which is the main theory of this study is examined. Later studies based on the Winkler approach are also mentioned. In addition, some differential equations and soil-foundation models related with spring concept are presented.

3. NUMERICAL ANALYSIS

3.1 Software Programs Used in the Study

PLAXIS and SAP2000 softwares have been used in numerical analysis phase of this study. PLAXIS will be dealt with first. PLAXIS is a finite element software program used for creating models which analyze the deformation, stability and the water flow for various types of geotechnical applications. Real problems can be modeled either by a plane strain or an axisymmetric model. The program uses a practical graphical user interface that provides to the users quickly creates a geometry model and finite element mesh based on a representative vertical cross section of the situation at hand.

The reason for choosing PLAXIS as the analysis program is that many properties of soil can be defined in this program. The other main reason of choosing the PLAXIS is this software computes the soil-foundation model by considering deformations and plastic properties of soil. Also, all effective stresses in soil media are compute by PLAXIS in different depths of soil by means of existence of meshes. Therefore, it is considered that a realistic soil-foundation analysis result will be obtained with PLAXIS software. Unit weights of soil (dry and saturated), permeability, void ratio, modulus of elasticity (Young’s modulus), Poisson’s ratio, shear modulus, cohesion and internal friction angle are some of definable properties of soil in PLAXIS. In order to suggest a simple and useful equation, also, since it is expected that mainly these properties affect the subgrade reaction modulus; only modulus of elasticity (Young’s modulus), Poisson’s ratio and shear strength parameters (c,ϕ) have been defined.

PLAXIS uses finite element method to compute the deflections and internal forces of soil or plates. Due to this requirement, meshes should be generated in the model. Since PLAXIS can compute the stresses and strains in two-dimensional plane, the program inputs are inserted as there is a 1-meter width model into the plane. While soil is defined in geometry lines, foundation members such as raft foundation or beam are defined as plate. Due to this situation, properties such as axial rigidity, flexural rigidity, thickness and Poisson's ratio of plate are input parameters. PLAXIS provides possibility that choosing the material models such as 'Linear elastic', 'Mohr-coulomb', 'Soft soil model', 'Hardening soil model', 'Soft soil creep model', 'Jointed rock model' and 'User-defined model'. In this study, Mohr-Coulomb model has been used. Mohr-Coulomb model is used as first approximation of soil behavior in general. Failure surface of this model based on Coulomb's friction law to general states of stress. As mentioned before, for the purpose of obtaining a simple equation; water level and drainage conditions have not been included in the model. PLAXIS output data provide the deformed shape of soil or plate, settlement value, effective or total stresses of soil and internal forces such as axial force, shear force, bending moment in plate (or beam). Most important output is selected to be the settlement of the foundation in this study.

SAP2000 is the second software that was utilized in this study. SAP2000 is a full-featured program that can be used for the simplest problems or the most complex projects. In fact, this program has been used for super-structure design frequently. However, there are no properties to define the soil other than the springs that behaves elastically under loading. Behavior of defined spring reflects the Hooke's law as can be examined in Figure-3.1 & Figure-3.2.

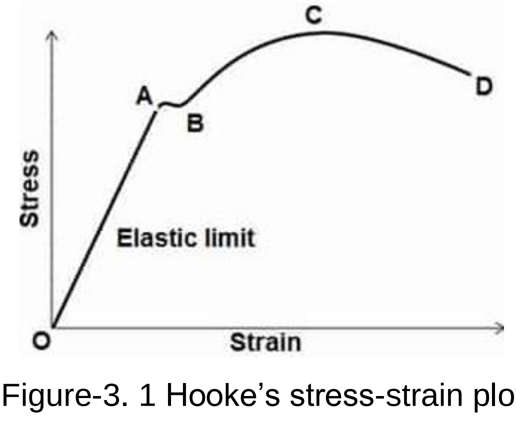


Figure-3. 1 Hooke's stress-strain plot

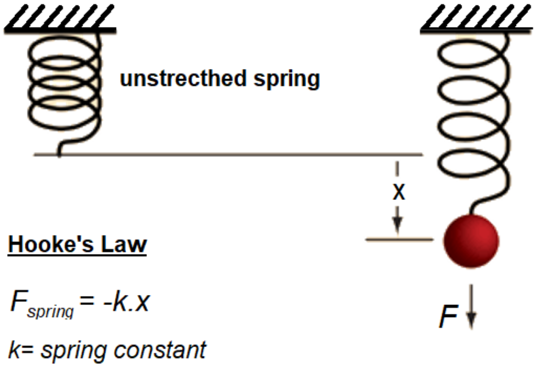


Figure-3. 2 Simple spring based on Hooke’s law

Most important issue about springs defined in SAP2000 is the fact that the spring will remain in ‘Elastic limit’ according to Figure-3.1. Therefore, when load applied to the spring increases, the extension of the spring will increase infinitely. Due to this situation, some differences (which will be mentioned later) between PLAXIS and SAP2000 models will arise. Structural members can be defined as frame, tendon, cable, area sections or solids in SAP2000. In this study, frame section has been preferred. Increasing the number of springs, the system will behave more realistically. For the purpose of providing this, a single frame member has been divided into smaller sections. To provide the Winkler foundation conditions, springs should be assigned to each joint between frame sections. Subgrade reaction modulus has been input into the program as spring constant in proportion to area to be loaded of each member. Output values such as shear force, bending moment and settlement obtained from SAP2000 will be compared with the results of PLAXIS.

The foundation member modeled in PLAXIS will be entered in the SAP2000 with the same geometric and material properties. Since the only parameter representing the soil that can be inserted in SAP2000 is spring constant, this value will be assumed as the value that gives the same settlement obtained from PLAXIS as a result of defined soil parameters.

3.2 Numerical Analyses

Before starting the analysis step of this study, the geometrical and mechanical properties of soil and foundation member have been determined hypothetically. Since PLAXIS software analyses in the two-dimensional plane, for the purpose of obtaining consistent results in both PLAXIS and SAP2000 softwares, a beam whose dimensions are assumed before, has been preferred as foundation member. It can be expected that 1m-width beam member modeled in SAP2000 will correspond to the plate member in PLAXIS.

Properties of soil and geometry of beam can be examined in Figure-3.3 and Figure-3.4. 100 kPa (kN/m²) uniformly distributed load has been chosen. As mentioned before, water table has not been considered in the soil medium.

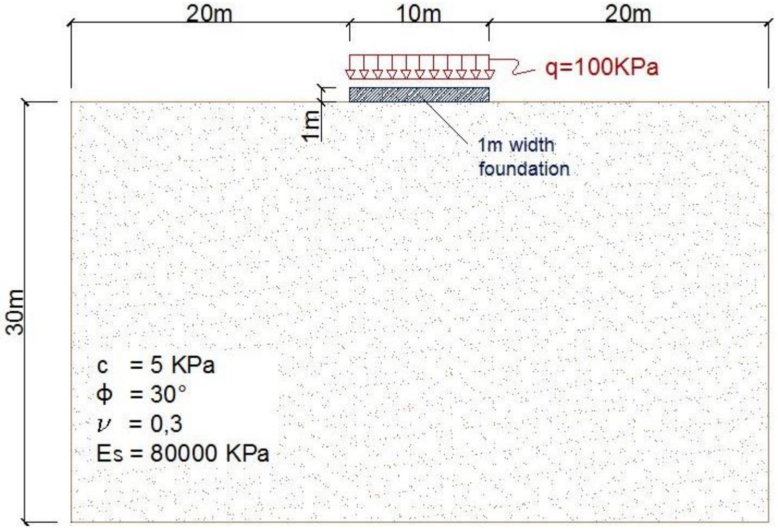


Figure-3. 3 Cross section of soil medium to be analyzed

Soil has been considered as single homogeneous layer. Depth of soil (30m) as can be seen in Figure-3.3 has been considered appropriate for finite element solutions in PLAXIS. Soil parameters have been assumed as preliminary parameters, and at the further analysis steps these will be altered. Material and mechanical properties of beam have been submitted below as can be seen in Table-3.1 and Table-3.2.

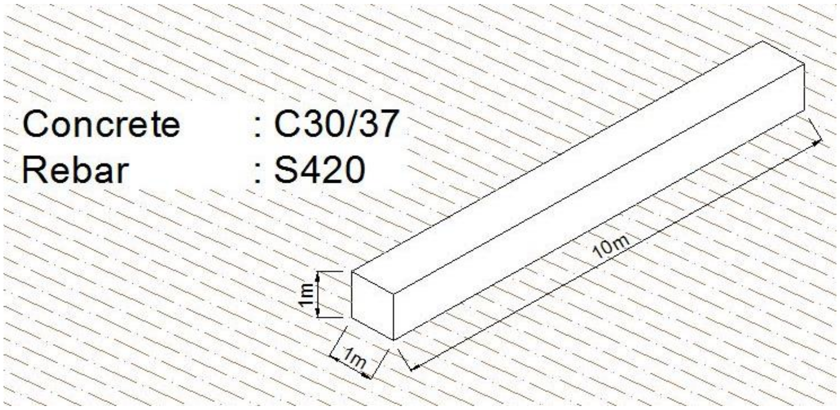


Figure-3. 4 General view of beam to be analyzed

Table-3. 1 Concrete Grades according to the Eurocode-2

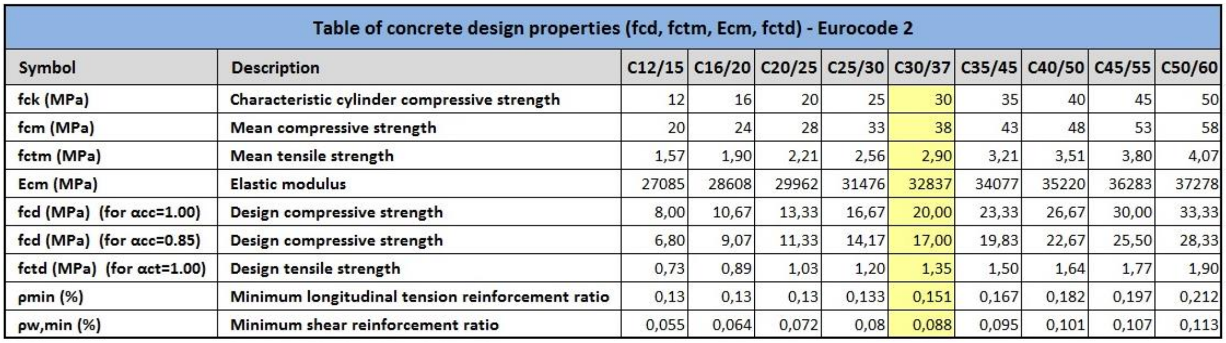
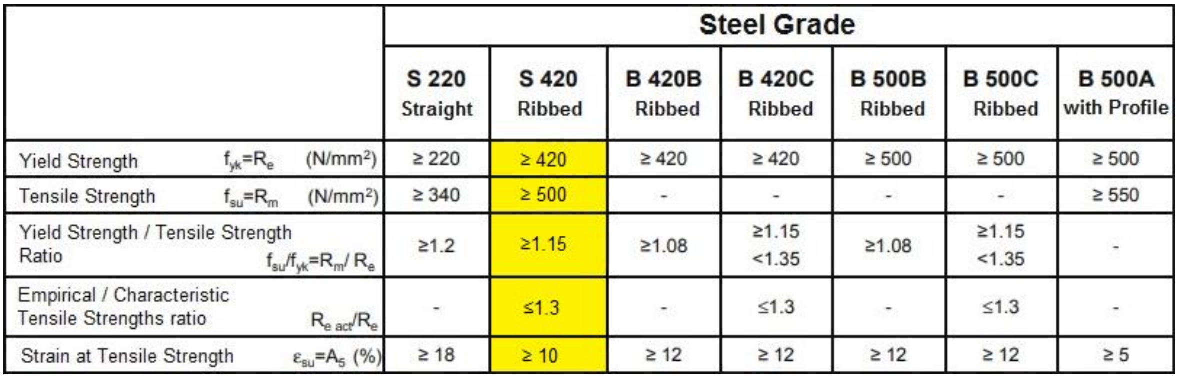


Table of concrete design properties (fcd, fctm, Ecm, fctd) - Eurocode 2										
Symbol	**Description**	**C12/15**	**C16/20**	**C20/25**	**C25/30**	**C30/37**	**C35/45**	**C40/50**	**C45/55**	**C50/60**
fck (MPa)	**Characteristic cylinder compressive strength**	12	16	20	25	30	35	40	45	50
fcm (MPa)	**Mean compressive strength**	20	24	28	33	38	43	48	53	58
fctm (MPa)	**Mean tensile strength**	1,57	1,90	2,21	2,56	2,90	3,21	3,51	3,80	4,07
Ecm (MPa)	**Elastic modulus**	27085	28608	29962	31476	32837	34077	35220	36283	37278
fcd (MPa) (for αcc=1.00)	**Design compressive strength**	8,00	10,67	13,33	16,67	20,00	23,33	26,67	30,00	33,33
fcd (MPa) (for αcc=0.85)	**Design compressive strength**	6,80	9,07	11,33	14,17	17,00	19,83	22,67	25,50	28,33
fctd (MPa) (for αct=1.00)	**Design tensile strength**	0,73	0,89	1,03	1,20	1,35	1,50	1,64	1,77	1,90
ρmin (%)	**Minimum longitudinal tension reinforcement ratio**	0,13	0,13	0,13	0,133	0,151	0,167	0,182	0,197	0,212
ρw,min (%)	**Minimum shear reinforcement ratio**	0,055	0,064	0,072	0,08	0,088	0,095	0,101	0,107	0,113

Concrete material of beam has been chosen as C30/37 according to Table-3.1. Steel rebar material of beam has been chosen as S420 according to Table-3.2. Although it is not expected that steel grade affect the behavior of beam, it was input for the purpose of SAP2000 can compute the model.

Table-3. 2 Mechanical properties of steel rebar for structures (TS 708:2010)



	Steel Grade						
	S 220 Straight	**S 420** Ribbed	**B 420B** Ribbed	**B 420C** Ribbed	**B 500B** Ribbed	**B 500C** Ribbed	**B 500A** with Profile
Yield Strength $f_{yk}=R_e$ (N/mm^2)	≥ 220	≥ 420	≥ 420	≥ 420	≥ 500	≥ 500	≥ 500
Tensile Strength $f_{su}=R_m$ (N/mm^2)	≥ 340	≥ 500	-	-	-	-	≥ 550
Yield Strength / Tensile Strength Ratio $f_{su}/f_{yk}=R_m/R_e$	≥1.2	≥1.15	≥1.08	≥1.15 <1.35	≥1.08	≥1.15 <1.35	-
Empirical / Characteristic Tensile Strengths ratio $R_{e\,act}/R_e$	-	≤1.3	-	≤1.3	-	≤1.3	-
Strain at Tensile Strength $\varepsilon_{su}=A_5$ (%)	≥ 18	≥ 10	≥ 12	≥ 12	≥ 12	≥ 12	≥ 5

At first, the PLAXIS analyses have been performed. Soil and beam properties mentioned before have been used in the analyses. Results of every individual analysis have been read and noted as can be seen in Figure-3.5 and Figure-3.6.

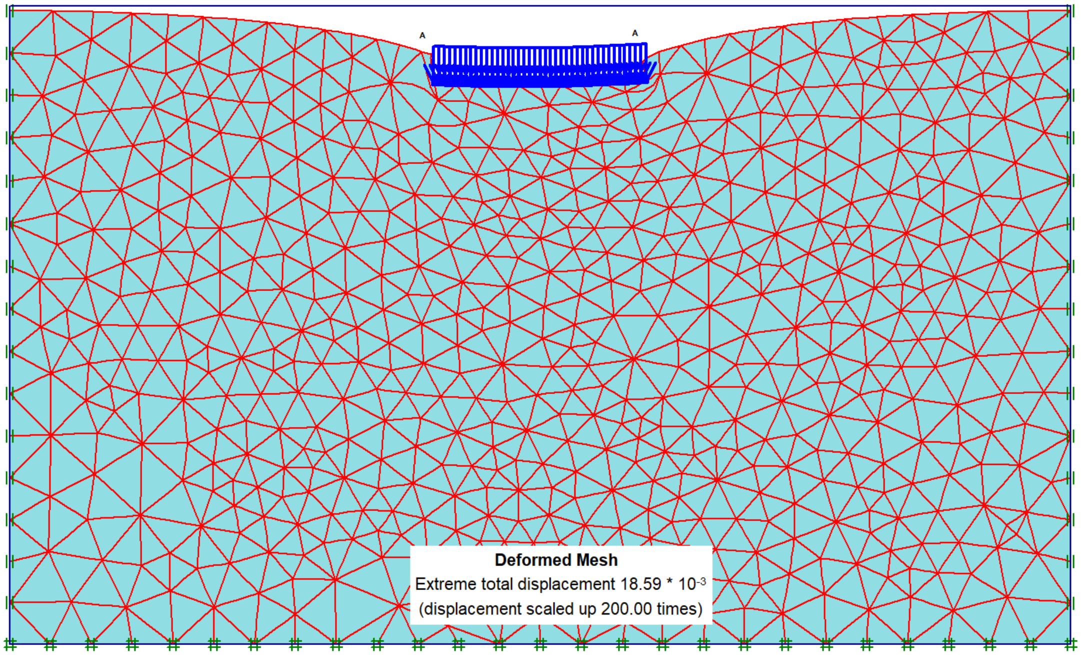
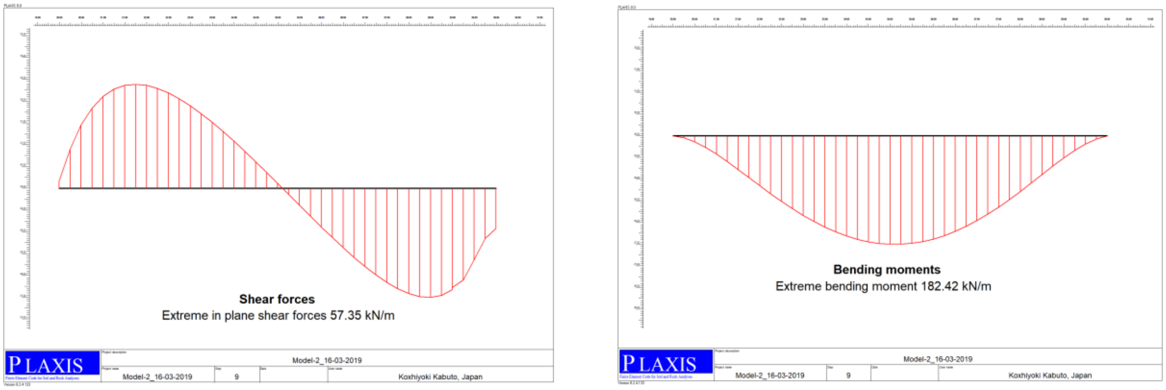


Figure-3. 5 Deformed shape of soil and maximum displacement of foundation



(a) Maximum shear force

(b) Maximum bending moment

Figure-3. 6 Initial analysis results in PLAXIS

Then, a beam with the same properties in the PLAXIS model has been modeled in SAP2000. Subgrade reaction modulus (spring constant) has initially been assumed as 10000kN/m³ (1000ton/m³). Beam whose dimensions are 1m width, 1m thickness and 10m length has been divided into 10 section (length of each one is 1m). Initially, dividing the beam into 10 sections has been chosen as random. According to the results of analyses, number of sections is changed. Due to the load area of each section is equal to the 1m² (1m length x 1m width = 1m²), each spring constant has been assigned as 10000kN/m (1m² x 10000kN/m³ = 10000kN/m). By considering direction concept of SAP2000, spring constant have been input with a minus sign (-10000kN/m). After that first analysis in SAP2000; settlement, shear force and bending moment values have been obtained as can be seen in Table-3.3 and Table-3.4.

Table-3. 3 Internal forces of beam after first analysis in SAP2000

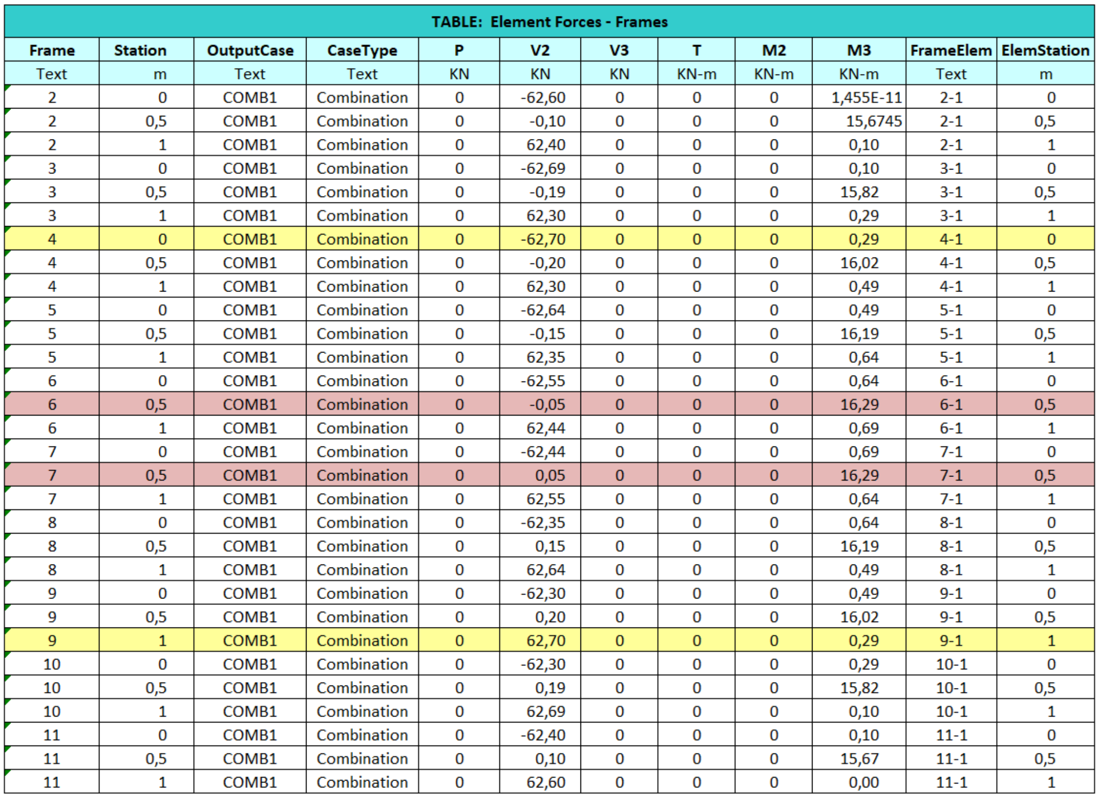


TABLE: Element Forces - Frames

Frame	Station	OutputCase	CaseType	P	V2	V3	T	M2	M3	FrameElem	ElemStation
Text	m	Text	Text	KN	KN	KN	KN-m	KN-m	KN-m	Text	m
2	0	COMB1	Combination	0	-62,60	0	0	0	1,455E-11	2-1	0
2	0,5	COMB1	Combination	0	-0,10	0	0	0	15,6745	2-1	0,5
2	1	COMB1	Combination	0	62,40	0	0	0	0,10	2-1	1
3	0	COMB1	Combination	0	-62,69	0	0	0	0,10	3-1	0
3	0,5	COMB1	Combination	0	-0,19	0	0	0	15,82	3-1	0,5
3	1	COMB1	Combination	0	62,30	0	0	0	0,29	3-1	1
4	0	COMB1	Combination	0	-62,70	0	0	0	0,29	4-1	0
4	0,5	COMB1	Combination	0	-0,20	0	0	0	16,02	4-1	0,5
4	1	COMB1	Combination	0	62,30	0	0	0	0,49	4-1	1
5	0	COMB1	Combination	0	-62,64	0	0	0	0,49	5-1	0
5	0,5	COMB1	Combination	0	-0,15	0	0	0	16,19	5-1	0,5
5	1	COMB1	Combination	0	62,35	0	0	0	0,64	5-1	1
6	0	COMB1	Combination	0	-62,55	0	0	0	0,64	6-1	0
6	0,5	COMB1	Combination	0	-0,05	0	0	0	16,29	6-1	0,5
6	1	COMB1	Combination	0	62,44	0	0	0	0,69	6-1	1
7	0	COMB1	Combination	0	-62,44	0	0	0	0,69	7-1	0
7	0,5	COMB1	Combination	0	0,05	0	0	0	16,29	7-1	0,5
7	1	COMB1	Combination	0	62,55	0	0	0	0,64	7-1	1
8	0	COMB1	Combination	0	-62,35	0	0	0	0,64	8-1	0
8	0,5	COMB1	Combination	0	0,15	0	0	0	16,19	8-1	0,5
8	1	COMB1	Combination	0	62,64	0	0	0	0,49	8-1	1
9	0	COMB1	Combination	0	-62,30	0	0	0	0,49	9-1	0
9	0,5	COMB1	Combination	0	0,20	0	0	0	16,02	9-1	0,5
9	1	COMB1	Combination	0	62,70	0	0	0	0,29	9-1	1
10	0	COMB1	Combination	0	-62,30	0	0	0	0,29	10-1	0
10	0,5	COMB1	Combination	0	0,19	0	0	0	15,82	10-1	0,5
10	1	COMB1	Combination	0	62,69	0	0	0	0,10	10-1	1
11	0	COMB1	Combination	0	-62,40	0	0	0	0,10	11-1	0
11	0,5	COMB1	Combination	0	0,10	0	0	0	15,67	11-1	0,5
11	1	COMB1	Combination	0	62,60	0	0	0	0,00	11-1	1

- Rows marked with yellow show maximum shear forces,
- Rows marked with red show the maximum bending moments

Table-3. 4 Joint displacements of beam after first analysis in SAP2000

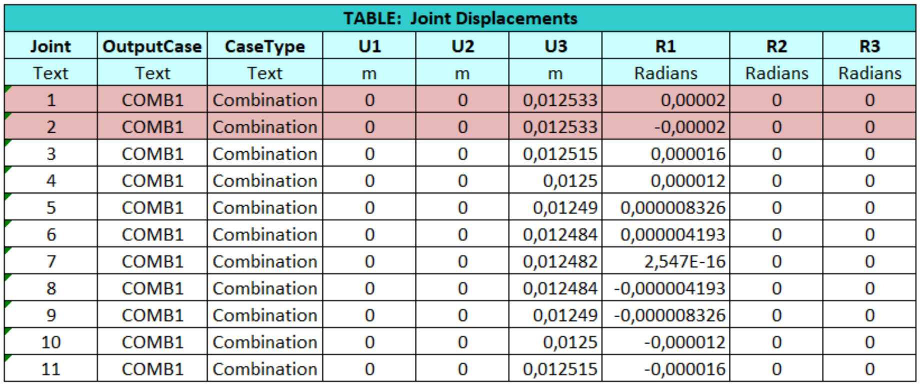


TABLE: Joint Displacements

Joint	OutputCase	CaseType	U1	U2	U3	R1	R2	R3
Text	Text	Text	m	m	m	Radians	Radians	Radians
1	COMB1	Combination	0	0	0,012533	0,00002	0	0
2	COMB1	Combination	0	0	0,012533	-0,00002	0	0
3	COMB1	Combination	0	0	0,012515	0,000016	0	0
4	COMB1	Combination	0	0	0,0125	0,000012	0	0
5	COMB1	Combination	0	0	0,01249	0,000008326	0	0
6	COMB1	Combination	0	0	0,012484	0,000004193	0	0
7	COMB1	Combination	0	0	0,012482	2,547E-16	0	0
8	COMB1	Combination	0	0	0,012484	-0,000004193	0	0
9	COMB1	Combination	0	0	0,01249	-0,000008326	0	0
10	COMB1	Combination	0	0	0,0125	-0,000012	0	0
11	COMB1	Combination	0	0	0,012515	-0,000016	0	0

- Rows marked with red show maximum joint displacements

Due to the only one parameter can be input in SAP2000 as the parameter to represent the soil is spring constant, it's expected that most important output data in terms of comparison is settlement (joint displacement). Accordingly, settlement results of initial analyses are compared firstly. Thus, as can be seen in Figure-3.5 and Table-3.4, there is a divergence between settlement values in PLAXIS and SAP2000. Proportionally with difference between two models, spring constant (subgrade reaction modulus) has been revised as 6162 kN/m and settlement value has been obtained in second analysis at SAP2000 as can be examined in Table-3.5.

Table-3. 5 Joint displacements of beam after second analysis in SAP2000

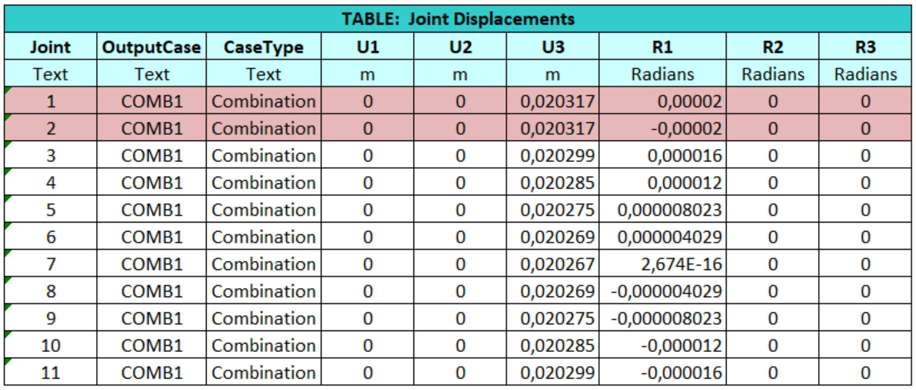
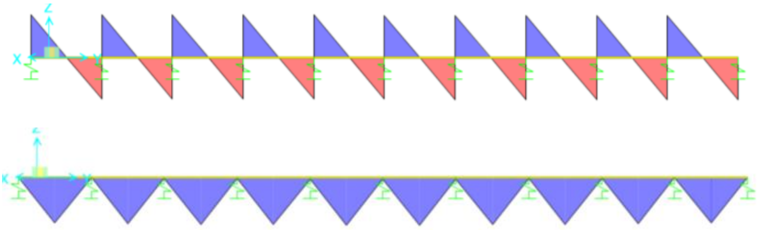


TABLE: Joint Displacements

Joint	OutputCase	CaseType	U1	U2	U3	R1	R2	R3
Text	Text	Text	m	m	m	Radians	Radians	Radians
1	COMB1	Combination	0	0	0,020317	0,00002	0	0
2	COMB1	Combination	0	0	0,020317	-0,00002	0	0
3	COMB1	Combination	0	0	0,020299	0,000016	0	0
4	COMB1	Combination	0	0	0,020285	0,000012	0	0
5	COMB1	Combination	0	0	0,020275	0,000008023	0	0
6	COMB1	Combination	0	0	0,020269	0,000004029	0	0
7	COMB1	Combination	0	0	0,020267	2,674E-16	0	0
8	COMB1	Combination	0	0	0,020269	-0,000004029	0	0
9	COMB1	Combination	0	0	0,020275	-0,000008023	0	0
10	COMB1	Combination	0	0	0,020285	-0,000012	0	0
11	COMB1	Combination	0	0	0,020299	-0,000016	0	0

- Rows marked with red show maximum joint displacements

By comparing Figure-3.5 and Table-3.5, it is observed that settlement values of both softwares have been approximated to each other. However, shear force and bending moment diagrams of both softwares are quite varying as can be examined in Figure-3.6 and Figure-3.7.

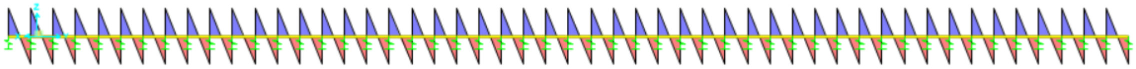


(a) Shear force diagram

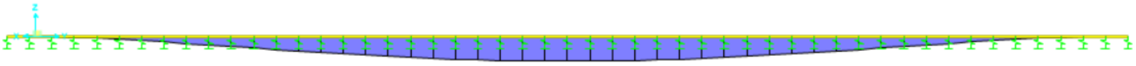
(b) Bending moment diagram

Figure-3. 7 Internal force diagrams after second analysis in SAP2000

By comparing the results obtained from these two different analyses; definitions such as support conditions, spring constants, divided frame sections, loads and directions have been reviewed and it has been tried to find the reason of dissimilarity between results of PLAXIS and SAP2000. Consequently, the beam has been divided into smaller sections (50 sections) in accordance with expressions in fifth paragraph of previous section ("*3.1 Software programs used in the study*"). Internal force diagrams of this analysis can be seen in Figure-3.8 as follows;



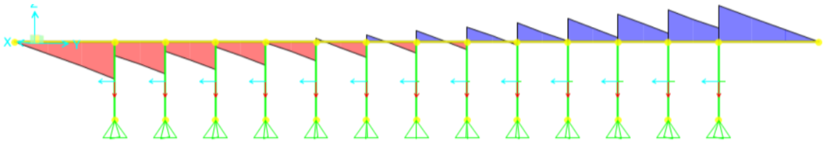
(a) Shear force diagram



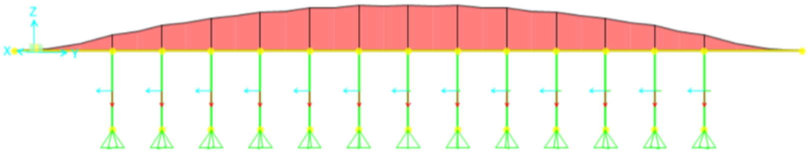
(b) Bending moment diagram

Figure-3. 8 Internal force diagrams after third step of analysis in SAP2000

However, it has been observed that by repeating the analyses, similar shear force diagram with previous analysis was obtained. Unlike shear force diagram, bending moment diagram has showed similar form with the one in PLAXIS as can be seen in Figure-3.6b and Figure-3.8b. Dissimilarity between shear diagrams has not been accepted and model has been revised. At the next step, for the purpose of obtaining a more accurate stress and deformation distribution, springs was changed with ‘links’, additionally start and end springs was removed in SAP2000 model. Links are members that transmit the deflections, rotations or forces with specific damping ratio. With this aspect, they show similar behavior to springs. Also, since existence of more structural member (sections) leads to more time-effort in analyzing process, beam was divided into 10 sections again for enable faster analysis process in SAP2000. After these modifications on the model and analysis, force diagrams have been obtained as can be seen in Figure-3.9;



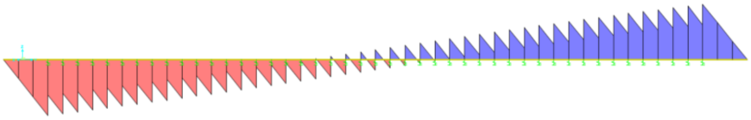
(a) Shear force diagram



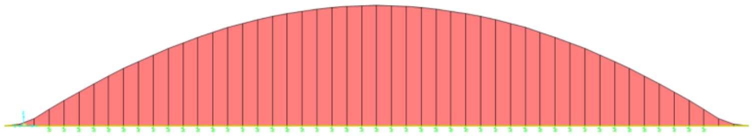
(b) Bending moment diagram

Figure-3. 9 Internal force diagrams after fourth step of analysis in SAP2000

As can be examined in Figure-3.6 and Figure-3.9, internal force diagram shapes of PLAXIS and SAP2000 has approximated to each other after fourth step of SAP2000 analysis. However, moment diagram of SAP2000 has remained at negative side. Since it is considered that there is no difference between springs and links as behavioral, links in last version (fourth step) of SAP2000 model have been changed with springs again, beam has been divided into 50 sections (to obtain more accurate results) and analysis has been repeated. After that, similar form with Figure-3.9 but more sensitive internal force diagrams have been obtained as can be seen in Figure-3.10;



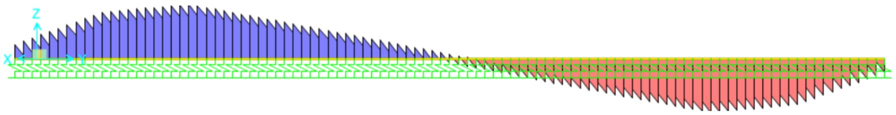
(a) Shear force diagram



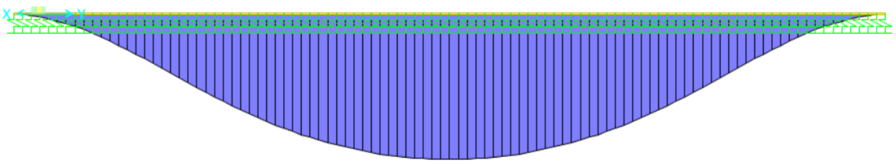
(b) Bending moment diagram

Figure-3. 10 Internal force diagrams after fifth step of analysis in SAP2000

As explained in Chapter 2 (Literature review), according to the approaches which proposed by Winkler (1867) and Bowles (1997), edge springs with more rigidity can be defined in model. Considering this, to obtain similar results with PLAXIS, it has been decided to creating the spring zones with more rigidity at the edges of beam initially. Subsequently, in accordance with expressions in fifth paragraph of Section 3.1 ("*…increasing the number of springs, the system will behave more realistically…*"), the beam have been divided into more sections (100 sections) and number of springs was increased. Eventually, similar shapes of internal force diagrams with PLAXIS model were obtained after these modifications on SAP2000 model. Internal force diagrams of this model can be seen in Figure-3.11.



(a) Shear force diagram

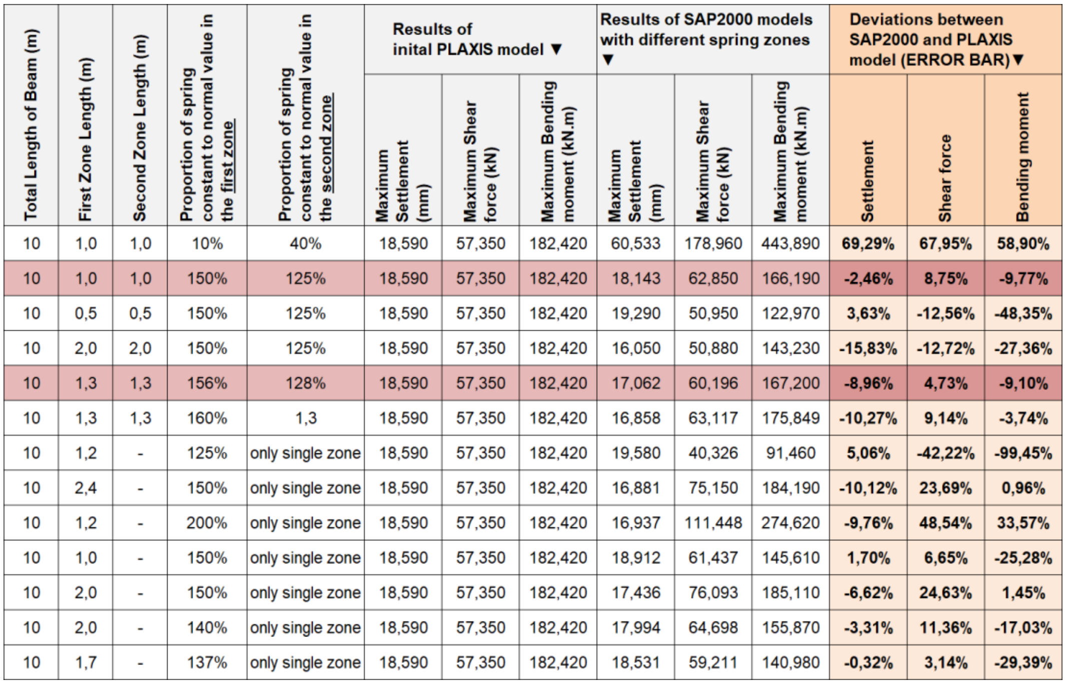


(b) Bending moment diagram

Figure-3. 11 Internal force diagrams after sixth step of analysis in SAP2000

However, it is not clear how to determine the lengths and the stiffness of the spring zones. To determine the lengths and the spring constants of the spring zones, many other variation of last version of the SAP2000 model (6th step) with different spring zone lengths and different spring constants has been analyzed. Comparison of the results is given in Table-3.6 below;

Table-3. 6 Comparison between initial PLAXIS model and SAP2000 models with different spring zones



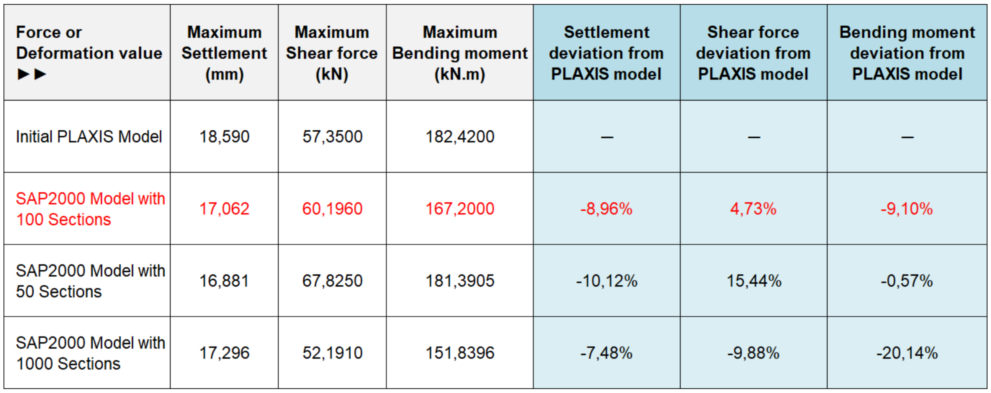
Total Length of Beam (m)	First Zone Length (m)	Second Zone Length (m)	Proportion of spring constant to normal value in the first zone	Proportion of spring constant to normal value in the second zone	Results of inital PLAXIS model ▼			Results of SAP2000 models with different spring zones ▼			Deviations between SAP2000 and PLAXIS model (ERROR BAR) ▼		
					Maximum Settlement (mm)	Maximum Shear force (kN)	Maximum Bending moment (kN.m)	Maximum Settlement (mm)	Maximum Shear force (kN)	Maximum Bending moment (kN.m)	Settlement	Shear force	Bending moment
10	1,0	1,0	10%	40%	18,590	57,350	182,420	60,533	178,960	443,890	**69,29%**	**67,95%**	**58,90%**
10	1,0	1,0	150%	125%	18,590	57,350	182,420	18,143	62,850	166,190	**-2,46%**	**8,75%**	**-9,77%**
10	0,5	0,5	150%	125%	18,590	57,350	182,420	19,290	50,950	122,970	**3,63%**	**-12,56%**	**-48,35%**
10	2,0	2,0	150%	125%	18,590	57,350	182,420	16,050	50,880	143,230	**-15,83%**	**-12,72%**	**-27,36%**
10	1,3	1,3	156%	128%	18,590	57,350	182,420	17,062	60,196	167,200	**-8,96%**	**4,73%**	**-9,10%**
10	1,3	1,3	160%	1,3	18,590	57,350	182,420	16,858	63,117	175,849	**-10,27%**	**9,14%**	**-3,74%**
10	1,2	-	125%	only single zone	18,590	57,350	182,420	19,580	40,326	91,460	**5,06%**	**-42,22%**	**-99,45%**
10	2,4	-	150%	only single zone	18,590	57,350	182,420	16,881	75,150	184,190	**-10,12%**	**23,69%**	**0,96%**
10	1,2	-	200%	only single zone	18,590	57,350	182,420	16,937	111,448	274,620	**-9,76%**	**48,54%**	**33,57%**
10	1,0	-	150%	only single zone	18,590	57,350	182,420	18,912	61,437	145,610	**1,70%**	**6,65%**	**-25,28%**
10	2,0	-	150%	only single zone	18,590	57,350	182,420	17,436	76,093	185,110	**-6,62%**	**24,63%**	**1,45%**
10	2,0	-	140%	only single zone	18,590	57,350	182,420	17,994	64,698	155,870	**-3,31%**	**11,36%**	**-17,03%**
10	1,7	-	137%	only single zone	18,590	57,350	182,420	18,531	59,211	140,980	**-0,32%**	**3,14%**	**-29,39%**

**There is no analysis/model in PLAXIS software with different spring zones. Spring zones was created in SAP2000 model for just obtain similar results with PLAXIS. The column "*Results of initial PLAXIS model*" in the table, added for the purpose of comparing with the SAP2000 results.

In Table-3.6, models with minimal deviation are showed by rows marked with red. Fourth column of the table shows the proportion of subgrade reaction modulus (spring constant) to normal value of subgrade reaction modulus 'k_s' in first zone, likewise fifth column shows the mentioned proportion in second zone. For instance; at the model in second row, spring constant is 150% (or 1.5 times) of normal value 'k_s' in first spring zone (*thus, meaning is that:* $k_{s1} = 1.5k_s$). According to these results, it can be observed that results of model whose spring constant at the first zone is 156% of normal value ($k_{s1}=1.56k_s$, $k_{s2}=1.28k_s$) has the most consistent deviation values. Because, although the deviations of the model in the second row ($k_{s1} = 1.5k_s$ and $k_{s2} = 1.25k_s$) seem to be numerically less than the values of the model in the fifth row, differences between deviations of model at the fifth row ($k_{s1}=1.56k_s$) are less in comparison with model in the second row. Thus, it is recommended that spring zones should be created in accordance with model at the fifth row ($k_{s1}=1.56k_s$, $k_{s2}=1.28k_s$).

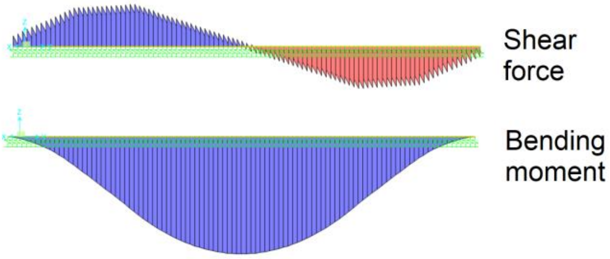
Furthermore, it was tried to determine how many sections the beam (or foundation) should be divided into. In addition to previously mentioned SAP2000 model (consists of 100 sections), models which consist of 50 sections and 1000 sections have been created analyzed respectively. The internal forces-deformations outputs and the deviations from PLAXIS model of these SAP2000 models are given in Table-3.7;

Table-3. 7 Comparison between PLAXIS and SAP2000 models with different number of sections

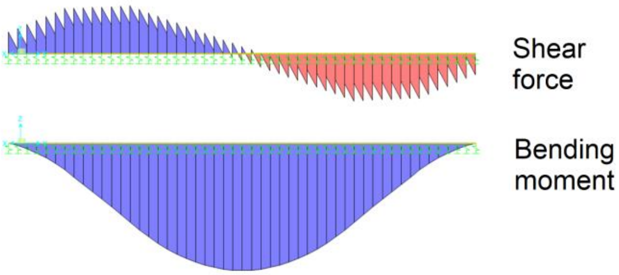


Force or Deformation value ►►	**Maximum Settlement (mm)**	**Maximum Shear force (kN)**	**Maximum Bending moment (kN.m)**	**Settlement deviation from PLAXIS model**	**Shear force deviation from PLAXIS model**	**Bending moment deviation from PLAXIS model**
Initial PLAXIS Model	18,590	57,3500	182,4200	–	–	–
SAP2000 Model with 100 Sections	17,062	60,1960	167,2000	-8,96%	4,73%	-9,10%
SAP2000 Model with 50 Sections	16,881	67,8250	181,3905	-10,12%	15,44%	-0,57%
SAP2000 Model with 1000 Sections	17,296	52,1910	151,8396	-7,48%	-9,88%	-20,14%

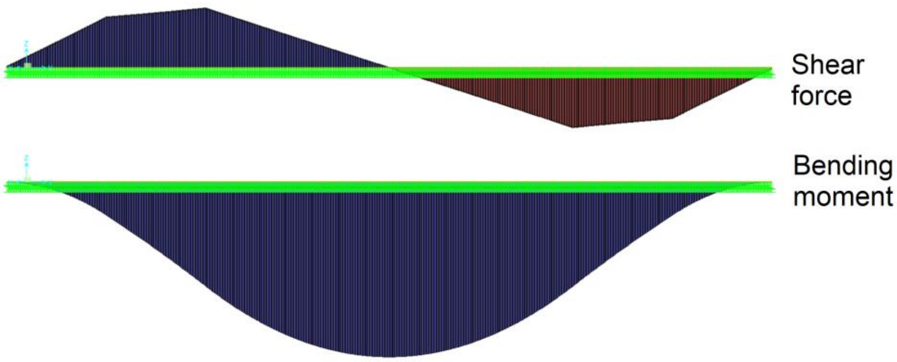
As can be seen in table above, there is not too much difference between deviations from PLAXIS model of all SAP2000 models whose number of sections is different. However, the least deviations were obtained from model with 100 sections. Moreover, as can be seen in Figure-3.12 below, there is no difference between forms of internal force diagrams of SAP2000 models with different number of sections.



(Model with 100 sections)



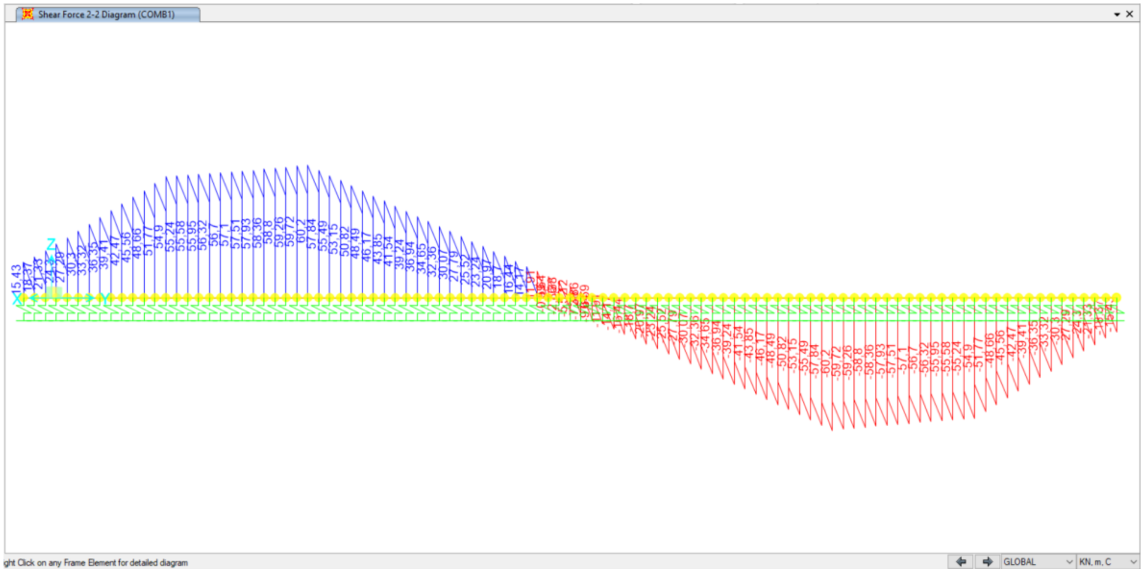
(Model with 50 sections)



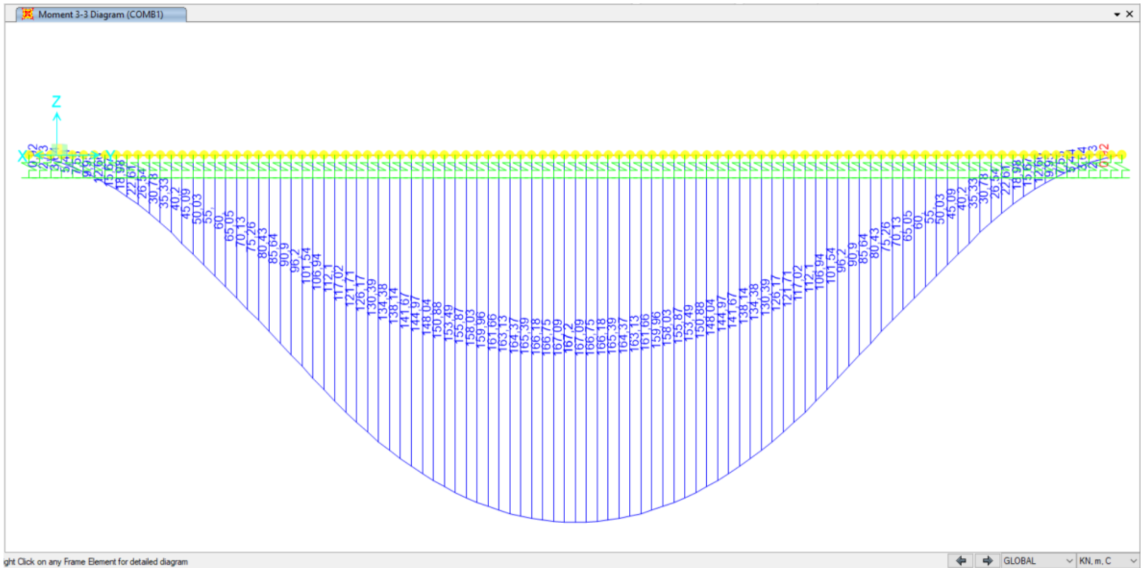
(Model with 1000 sections)

Figure-3. 12 Internal force diagrams of models with different number of sections

It should be remembered that if there is more structural members (sections), time period of analysis is increased. In accordance with all of these situations, it is recommended that foundation member should be divided into sections which dimensions are 1% (100 sections) of own width (or length). Internal force diagrams of SAP2000 model (11th step of analysis) with $k_{s1}=1.56k_s$, $k_{s2}=1.28k_s$ and 100 sections are given in Figure-3.12;



(a) Shear force diagram with numerical values

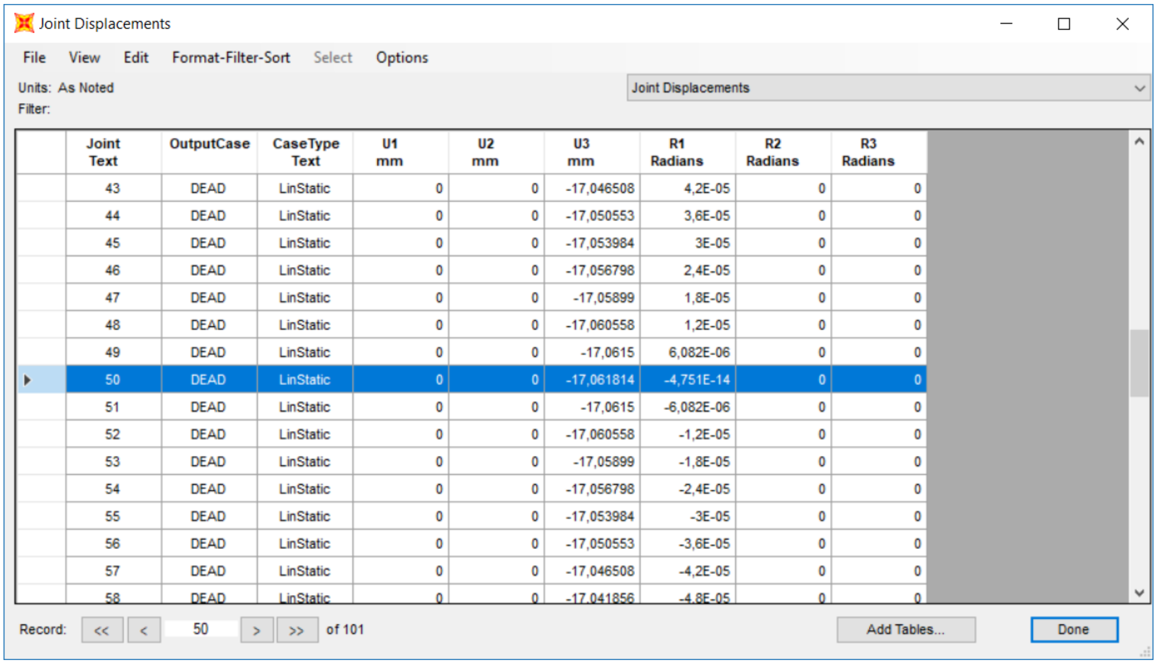


(b) Bending moment diagram with numerical values

Figure-3. 13 Internal force diagrams of 11th version of SAP2000 model

Additionally; maximum settlement, maximum shear force and bending moment values obtained from 11th analysis of SAP2000 model are given in tabular form as can be seen in Table-3.8 through Table-3.10;

Table-3. 8 Joint displacements of the 11th version of SAP2000 model



Units: As Noted

Filter:

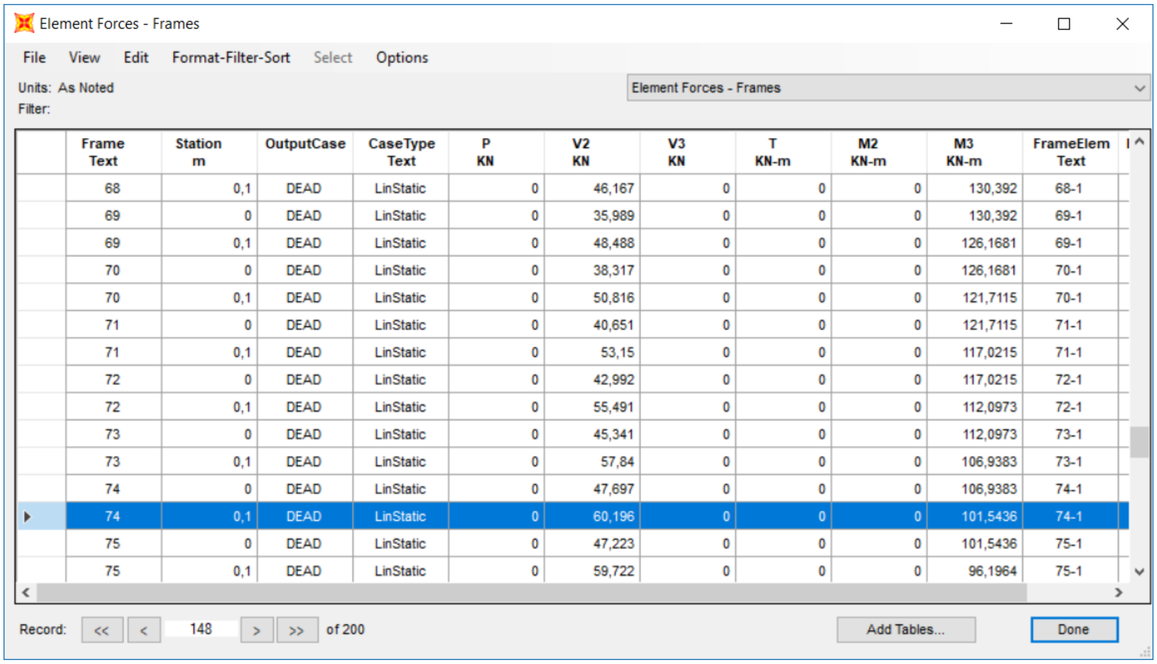
Joint Displacements

Joint Text	OutputCase	CaseType Text	U1 mm	U2 mm	U3 mm	R1 Radians	R2 Radians	R3 Radians
43	DEAD	LinStatic	0	0	-17,046508	4,2E-05	0	0
44	DEAD	LinStatic	0	0	-17,050553	3,6E-05	0	0
45	DEAD	LinStatic	0	0	-17,053984	3E-05	0	0
46	DEAD	LinStatic	0	0	-17,056798	2,4E-05	0	0
47	DEAD	LinStatic	0	0	-17,05899	1,8E-05	0	0
48	DEAD	LinStatic	0	0	-17,060558	1,2E-05	0	0
49	DEAD	LinStatic	0	0	-17,0615	6,082E-06	0	0
50	DEAD	LinStatic	0	0	-17,061814	-4,751E-14	0	0
51	DEAD	LinStatic	0	0	-17,0615	-6,082E-06	0	0
52	DEAD	LinStatic	0	0	-17,060558	-1,2E-05	0	0
53	DEAD	LinStatic	0	0	-17,05899	-1,8E-05	0	0
54	DEAD	LinStatic	0	0	-17,056798	-2,4E-05	0	0
55	DEAD	LinStatic	0	0	-17,053984	-3E-05	0	0
56	DEAD	LinStatic	0	0	-17,050553	-3,6E-05	0	0
57	DEAD	LinStatic	0	0	-17,046508	-4,2E-05	0	0
58	DEAD	LinStatic	0	0	-17,041856	-4,8E-05	0	0

Record: 50 of 101

- Blue line shows the maximum value. ‘U3’ means that joint displacement in vertical direction

Table-3. 9 Shear forces of the 11th version of SAP2000 model



Units: As Noted

Filter:

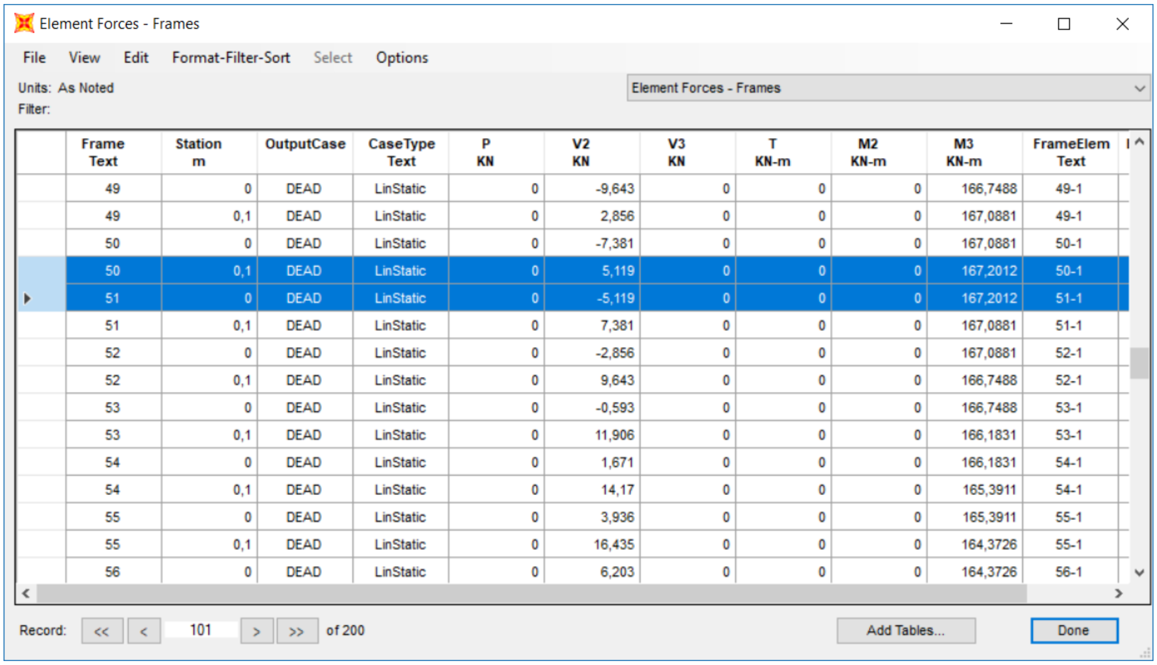
Element Forces - Frames

Frame Text	Station m	OutputCase	CaseType Text	P KN	V2 KN	V3 KN	T KN-m	M2 KN-m	M3 KN-m	FrameElem Text
68	0,1	DEAD	LinStatic	0	46,167	0	0	0	130,392	68-1
69	0	DEAD	LinStatic	0	35,989	0	0	0	130,392	69-1
69	0,1	DEAD	LinStatic	0	48,488	0	0	0	126,1681	69-1
70	0	DEAD	LinStatic	0	38,317	0	0	0	126,1681	70-1
70	0,1	DEAD	LinStatic	0	50,816	0	0	0	121,7115	70-1
71	0	DEAD	LinStatic	0	40,651	0	0	0	121,7115	71-1
71	0,1	DEAD	LinStatic	0	53,15	0	0	0	117,0215	71-1
72	0	DEAD	LinStatic	0	42,992	0	0	0	117,0215	72-1
72	0,1	DEAD	LinStatic	0	55,491	0	0	0	112,0973	72-1
73	0	DEAD	LinStatic	0	45,341	0	0	0	112,0973	73-1
73	0,1	DEAD	LinStatic	0	57,84	0	0	0	106,9383	73-1
74	0	DEAD	LinStatic	0	47,697	0	0	0	106,9383	74-1
74	0,1	DEAD	LinStatic	0	60,196	0	0	0	101,5436	74-1
75	0	DEAD	LinStatic	0	47,223	0	0	0	101,5436	75-1
75	0,1	DEAD	LinStatic	0	59,722	0	0	0	96,1964	75-1

Record: 148 of 200

- Blue line shows the maximum value. ‘V2’ means that shear force at beam section

Table-3. 10 Bending moments of the 11th version of SAP2000 model



Units: As Noted
Filter:

Frame Text	Station m	OutputCase	CaseType Text	P KN	V2 KN	V3 KN	T KN-m	M2 KN-m	M3 KN-m	FrameElem Text
49	0	DEAD	LinStatic	0	-9,643	0	0	0	166,7488	49-1
49	0,1	DEAD	LinStatic	0	2,856	0	0	0	167,0881	49-1
50	0	DEAD	LinStatic	0	-7,381	0	0	0	167,0881	50-1
50	0,1	DEAD	LinStatic	0	5,119	0	0	0	167,2012	50-1
51	0	DEAD	LinStatic	0	-5,119	0	0	0	167,2012	51-1
51	0,1	DEAD	LinStatic	0	7,381	0	0	0	167,0881	51-1
52	0	DEAD	LinStatic	0	-2,856	0	0	0	167,0881	52-1
52	0,1	DEAD	LinStatic	0	9,643	0	0	0	166,7488	52-1
53	0	DEAD	LinStatic	0	-0,593	0	0	0	166,7488	53-1
53	0,1	DEAD	LinStatic	0	11,906	0	0	0	166,1831	53-1
54	0	DEAD	LinStatic	0	1,671	0	0	0	166,1831	54-1
54	0,1	DEAD	LinStatic	0	14,17	0	0	0	165,3911	54-1
55	0	DEAD	LinStatic	0	3,936	0	0	0	165,3911	55-1
55	0,1	DEAD	LinStatic	0	16,435	0	0	0	164,3726	55-1
56	0	DEAD	LinStatic	0	6,203	0	0	0	164,3726	56-1

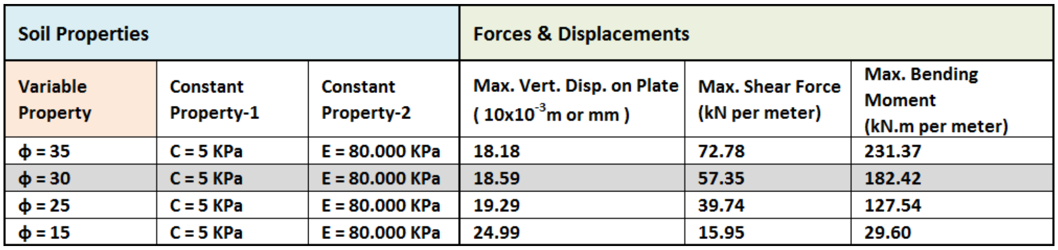
Record: << < 101 > >> of 200

- Blue line shows the maximum values. ‘M3’ means that bending moment at beam section

Due to the reasons explained previously, reference SAP2000 model which corresponds to the first PLAXIS model has been accepted as 11th version of SAP2000 model. 10% deviation of results between SAP2000 and PLAXIS models has been accepted as negligible (All results of the 11th version is given in Table-3.8 through Table.3-10 and Figure.3-13).

As mentioned before, initial PLAXIS model and 11th version of SAP2000 model have been assumed as equivalent. After this phase of analyses, parameters such as soil or geometrical properties of foundation was modified in PLAXIS and a SAP2000 model that corresponds to that was derived. At the commencement, derivations have been applied on model whose length is 10m and width & thickness are 1m and first parameter to be changed has been chosen as internal friction angle ‘ϕ’. Results of first derivation in PLAXIS are given in Table-3.11;

Table-3. 11 Results of different ‘ϕ’ values in PLAXIS (10m Length, 1m thickness)

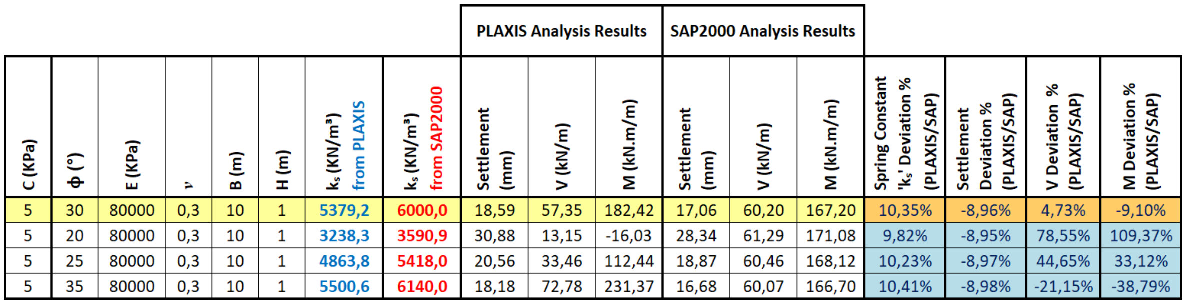


Soil Properties			**Forces & Displacements**		
Variable Property	**Constant Property-1**	**Constant Property-2**	**Max. Vert. Disp. on Plate (10x10^{-3}m or mm)**	**Max. Shear Force (kN per meter)**	**Max. Bending Moment (kN.m per meter)**
ϕ = 35	**C = 5 KPa**	**E = 80.000 KPa**	**18.18**	**72.78**	**231.37**
ϕ = 30	**C = 5 KPa**	**E = 80.000 KPa**	**18.59**	**57.35**	**182.42**
ϕ = 25	**C = 5 KPa**	**E = 80.000 KPa**	**19.29**	**39.74**	**127.54**
ϕ = 15	**C = 5 KPa**	**E = 80.000 KPa**	**24.99**	**15.95**	**29.60**

- Row marked with gray shows the initial input data

However, after analysis of SAP2000 models that corresponds to PLAXIS models with different ϕ, it has been observed that deviations of the shear force and the bending moment are quite higher than the deviation of settlement values as can be seen in Table-3.12;

Table-3. 12 Result comparison of PLAXIS and SAP in case ϕ is variable



								PLAXIS Analysis Results			**SAP2000 Analysis Results**						
C (KPa)	**ϕ (°)**	**E (KPa)**	**ν**	**B (m)**	**H (m)**	**k_s (KN/m³) from PLAXIS**	**k_s (KN/m³) from SAP2000**	**Settlement (mm)**	**V (kN/m)**	**M (kN.m/m)**	**Settlement (mm)**	**V (kN/m)**	**M (kN.m/m)**	**Spring Constant 'k_s' Deviation % (PLAXIS/SAP)**	**Settlement Deviation % (PLAXIS/SAP)**	**V Deviation % (PLAXIS/SAP)**	**M Deviation % (PLAXIS/SAP)**
5	30	80000	0,3	10	1	5379,2	6000,0	18,59	57,35	182,42	17,06	60,20	167,20	10,35%	-8,96%	4,73%	-9,10%
5	20	80000	0,3	10	1	3238,3	3590,9	30,88	13,15	-16,03	28,34	61,29	171,08	9,82%	-8,95%	78,55%	109,37%
5	25	80000	0,3	10	1	4863,8	5418,0	20,56	33,46	112,44	18,87	60,46	168,12	10,23%	-8,97%	44,65%	33,12%
5	35	80000	0,3	10	1	5500,6	6140,0	18,18	72,78	231,37	16,68	60,07	166,70	10,41%	-8,98%	-21,15%	-38,79%

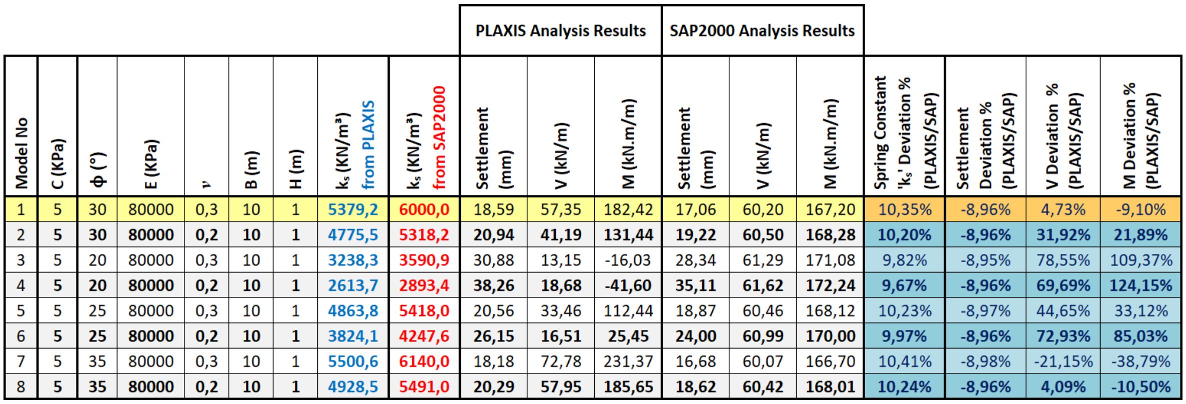
- Row marked with yellow shows the results of reference model

- Spring constant is obtained by formula ‘ks=Δσ/Δδ’ (pressure/displacement) in PLAXIS

By observing Table-3.12, while spring constant value is changed, although settlement value has changed proportional with PLAXIS in SAP2000 models, shear force and bending moment has not been changed much. This situation has been interpreted as result of ratio between spring constants of different spring zones are not changed in SAP2000 models. In more detail, spring constant of first zone is 1.56 times of normal value (middle zone) and spring constant of second zone is 1.28 times of normal value (middle zone). Even if the spring constant value changes numerically, the proportion between the spring constants of the first and second zone and the central zone remains constant. Therefore, there is no change in rigidity between the first and second zones and the middle zone. It has been considered that this situation leads to the shear forces and the bending moments remain as constant approximately.

After this phase, deviations in shear force and bending moment have not been taken into consideration and analyses have been continued considering the consistency of settlement (joint displacement) values. Internal friction angle ‘ϕ’, cohesion ‘c’ and modulus of elasticity ‘E’ values have been altered on model whose dimensions of beam are Width=10m, Thickness=1m in PLAXIS. These analyses have been done according to the Poisson’s ratio of soil ‘*ν*’ equals to the 0.3. All of these analyses have also been repeated according to the Poisson’s ratio ‘*ν*=0.2’ and different dimensions of beam. A model corresponding to each settlement value in PLAXIS has been created and analyzed in SAP2000 with changing the spring constant (subgrade reaction modulus). Also, variation of settlement value as percentage between derived and reference models in PLAXIS has been tried to keep in SAP2000. The analysis results are provided in Table-3.13 through Table-3.30. Spring constant is obtained by formula ‘$k_s = \Delta\sigma / \Delta\delta$’ (pressure/displacement) in PLAXIS software.

Table-3. 13 Analysis results of the beam: B=10m, H=1m, ‘ϕ’ & ‘*v*’ are variable



									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
1	5	30	80000	0,3	10	1	5379,2	6000,0	18,59	57,35	182,42	17,06	60,20	167,20	10,35%	-8,96%	4,73%	-9,10%
2	**5**	**30**	**80000**	**0,2**	**10**	**1**	**4775,5**	**5318,2**	**20,94**	**41,19**	**131,44**	**19,22**	**60,50**	**168,28**	**10,20%**	**-8,96%**	**31,92%**	**21,89%**
3	5	20	80000	0,3	10	1	3238,3	3590,9	30,88	13,15	-16,03	28,34	61,29	171,08	9,82%	-8,95%	78,55%	109,37%
4	**5**	**20**	**80000**	**0,2**	**10**	**1**	**2613,7**	**2893,4**	**38,26**	**18,68**	**-41,60**	**35,11**	**61,62**	**172,24**	**9,67%**	**-8,96%**	**69,69%**	**124,15%**
5	5	25	80000	0,3	10	1	4863,8	5418,0	20,56	33,46	112,44	18,87	60,46	168,12	10,23%	-8,97%	44,65%	33,12%
6	**5**	**25**	**80000**	**0,2**	**10**	**1**	**3824,1**	**4247,6**	**26,15**	**16,51**	**25,45**	**24,00**	**60,99**	**170,00**	**9,97%**	**-8,96%**	**72,93%**	**85,03%**
7	5	35	80000	0,3	10	1	5500,6	6140,0	18,18	72,78	231,37	16,68	60,07	166,70	10,41%	-8,98%	-21,15%	-38,79%
8	**5**	**35**	**80000**	**0,2**	**10**	**1**	**4928,5**	**5491,0**	**20,29**	**57,95**	**185,65**	**18,62**	**60,42**	**168,01**	**10,24%**	**-8,96%**	**4,09%**	**-10,50%**

Row marked with yellow shows the results of reference model for dimensions: B=10m, H=1m

Table-3. 14 Analysis results of the beam: B=10m, H=1m, ‘c’ & ‘v’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
9	10	30	80000	0,3	10	1	5509,6	6150,0	18,15	70,78	227,86	16,66	60,08	166,82	10,41%	-8,98%	-17,81%	-36,59%
10	**10**	**30**	**80000**	**0,2**	**10**	**1**	**4945,6**	**5505,0**	**20,22**	**56,60**	**183,34**	**18,55**	**60,87**	**169,77**	**10,16%**	**-8,99%**	**7,01%**	**-7,99%**
11	20	30	80000	0,3	10	1	5621,1	6275,0	17,79	86,46	277,53	16,33	60,07	166,77	10,42%	-8,97%	-43,92%	-66,42%
12	**20**	**30**	**80000**	**0,2**	**10**	**1**	**5096,8**	**5681,0**	**19,62**	**76,62**	**248,29**	**18,01**	**60,34**	**167,70**	**10,28%**	**-8,96%**	**-26,98%**	**-48,05%**
13	50	30	80000	0,3	10	1	5678,6	6340,0	17,61	96,84	305,21	16,16	60,04	166,66	10,43%	-8,97%	-61,29%	-83,14%
14	**50**	**30**	**80000**	**0,2**	**10**	**1**	**5168,0**	**5761,0**	**19,35**	**89,94**	**284,79**	**17,76**	**60,30**	**167,58**	**10,29%**	**-8,96%**	**-49,15%**	**-69,94%**

Table-3. 15 Analysis results of the beam: B=10m, H=1m, ‘E’ & ‘*v*’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
17	5	30	40000	0,3	10	1	2699,8	2990,0	37,04	62,12	198,62	33,99	61,57	172,07	9,71%	-8,98%	-0,89%	-15,43%
18	**5**	**30**	**40000**	**0,2**	**10**	**1**	**2390,6**	**2645,0**	**41,83**	**44,87**	**143,46**	**38,39**	**61,74**	**172,65**	**9,62%**	**-8,97%**	**27,32%**	**16,91%**
19	5	30	100000	0,3	10	1	6706,9	7510,0	14,91	55,14	174,90	13,68	59,53	164,86	10,69%	-9,00%	7,38%	-6,09%
20	**5**	**30**	**100000**	**0,2**	**10**	**1**	**5963,0**	**6662,0**	**16,77**	**39,67**	**126,47**	**15,39**	**59,90**	**166,17**	**10,49%**	**-8,97%**	**33,78%**	**23,89%**
21	5	30	150000	0,3	10	1	10000,0	11280,0	10,00	50,35	158,64	9,18	57,96	159,28	11,35%	-8,90%	13,13%	0,40%
22	**5**	**30**	**150000**	**0,2**	**10**	**1**	**8920,6**	**10040,0**	**11,21**	**36,32**	**115,50**	**10,29**	**58,46**	**161,08**	**11,15%**	**-8,94%**	**37,88%**	**28,29%**
23	5	30	200000	0,3	10	1	13315,6	15140,0	7,51	48,58	152,71	6,90	56,45	153,95	12,05%	-8,90%	13,94%	0,80%
24	**5**	**30**	**200000**	**0,2**	**10**	**1**	**11876,5**	**13470,0**	**8,42**	**33,60**	**106,63**	**7,73**	**57,09**	**156,22**	**11,83%**	**-9,00%**	**41,14%**	**31,74%**

Table-3. 16 Analysis results of the beam: B=10m, H=0.5m, ‘ϕ’ & ‘*v*’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
25	5	30	80000	0,3	10	0,5	5216,5	5582,0	19,17	28,26	82,29	17,59	43,03	111,00	6,55%	-8,98%	34,32%	25,86%
26	**5**	**30**	**80000**	**0,2**	**10**	**0,5**	**4694,8**	**4996,0**	**21,30**	**20,33**	**61,81**	**19,54**	**44,06**	**114,67**	**6,03%**	**-9,00%**	**53,86%**	**46,10%**
27	5	20	80000	0,3	10	0,5	3219,6	3363,0	31,06	12,08	-10,65	28,50	47,34	126,29	4,26%	-8,98%	74,48%	108,43%
28	**5**	**20**	**80000**	**0,2**	**10**	**0,5**	**2576,0**	**2666,0**	**38,82**	**13,75**	**-20,76**	**35,62**	**48,95**	**131,99**	**3,38%**	**-8,97%**	**71,91%**	**115,73%**
29	5	25	80000	0,3	10	0,5	4710,3	5013,8	21,23	19,68	46,84	19,48	44,03	114,56	6,05%	-9,01%	55,30%	59,11%
30	**5**	**25**	**80000**	**0,2**	**10**	**0,5**	**3849,1**	**4054,0**	**25,98**	**16,11**	**15,46**	**23,84**	**45,88**	**121,10**	**5,05%**	**-8,98%**	**64,89%**	**87,23%**
31	5	35	80000	0,3	10	0,5	5271,5	5644,0	18,97	35,33	97,00	17,41	42,92	110,63	6,60%	-8,97%	17,68%	12,32%
32	**5**	**35**	**80000**	**0,2**	**10**	**0,5**	**4812,3**	**5126,0**	**20,78**	**29,01**	**83,39**	**19,07**	**43,83**	**113,84**	**6,12%**	**-8,96%**	**33,81%**	**26,75%**

Row marked with yellow shows the results of reference model for dimensions: B=10m, H=0.5m

Table-3. 17 Analysis results of the beam : B=10m, H=0.5m, ‘c’ & ‘*v*’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
33	10	30	80000	0,3	10	0,5	5271,5	5644,0	18,97	34,56	96,62	17,41	42,92	110,63	6,60%	-8,97%	19,48%	12,66%
34	**10**	**30**	**80000**	**0,2**	**10**	**0,5**	**4805,4**	**5120,0**	**20,81**	**27,52**	**81,41**	**19,09**	**43,84**	**113,88**	**6,14%**	**-9,00%**	**37,22%**	**28,51%**
35	20	30	80000	0,3	10	0,5	5390,8	5778,7	18,55	42,10	108,51	17,02	42,69	109,83	6,71%	-8,96%	1,39%	1,20%
36	**20**	**30**	**80000**	**0,2**	**10**	**0,5**	**4870,9**	**5192,0**	**20,53**	**37,12**	**100,02**	**18,84**	**43,71**	**113,42**	**6,18%**	**-8,96%**	**15,07%**	**11,81%**
37	50	30	80000	0,3	10	0,5	5316,3	5695,0	18,81	47,01	113,00	17,26	42,80	110,15	6,65%	-8,96%	-9,85%	-2,58%
38	**50**	**30**	**80000**	**0,2**	**10**	**0,5**	**4890,0**	**5215,2**	**20,45**	**42,50**	**106,48**	**18,76**	**43,67**	**113,27**	**6,24%**	**-9,00%**	**2,67%**	**6,00%**

Table-3. 18 Analysis results of the beam: B=10m, H=0.5m, ‘E’ & ‘*v*’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
39	5	30	40000	0,3	10	0,5	2638,5	2733,0	37,90	39,19	120,63	34,78	48,79	131,42	3,46%	-8,96%	19,68%	8,21%
40	**5**	**30**	**40000**	**0,2**	**10**	**0,5**	**2364,1**	**2438,0**	**42,30**	**28,38**	**89,01**	**38,83**	**49,51**	**133,96**	**3,03%**	**-8,93%**	**42,68%**	**33,56%**
41	5	30	100000	0,3	10	0,5	6497,7	7042,0	15,39	25,09	70,67	14,12	40,71	102,81	7,73%	-8,97%	38,37%	31,26%
42	**5**	**30**	**100000**	**0,2**	**10**	**0,5**	**5858,2**	**6314,0**	**17,07**	**18,06**	**53,58**	**15,66**	**41,82**	**106,74**	**7,22%**	**-9,03%**	**56,81%**	**49,80%**
43	5	30	150000	0,3	10	0,5	9689,9	10766,0	10,32	19,83	51,86	9,47	36,09	86,49	10,00%	-8,98%	45,06%	40,04%
44	**5**	**30**	**150000**	**0,2**	**10**	**0,5**	**8748,9**	**9656,0**	**11,43**	**16,42**	**39,71**	**10,49**	**37,31**	**90,79**	**9,39%**	**-8,95%**	**55,99%**	**56,26%**
45	5	30	200000	0,3	10	0,5	12870,0	14550,0	7,77	16,95	40,70	7,14	32,69	74,44	11,55%	-8,90%	48,14%	45,33%
46	**5**	**30**	**200000**	**0,2**	**10**	**0,5**	**11641,4**	**13075,0**	**8,59**	**16,20**	**31,51**	**7,89**	**33,90**	**78,72**	**10,96%**	**-8,89%**	**52,21%**	**59,97%**

Table-3. 19 Analysis results of the beam: B=5m, H=1m, ‘ϕ’ & ‘*v*’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
47	5	30	80000	0,3	5	1	7898,9	8692,0	12,66	31,02	51,38	11,62	31,36	44,04	9,12%	-8,95%	1,09%	-16,66%
48	**5**	**30**	**80000**	**0,2**	**5**	**1**	**7037,3**	**7744,0**	**14,21**	**21,38**	**35,39**	**13,04**	**31,38**	**44,07**	**9,13%**	**-8,98%**	**31,87%**	**19,70%**
49	5	20	80000	0,3	5	1	4180,6	4596,6	23,92	13,93	-14,84	21,96	31,44	44,16	9,05%	-8,95%	55,69%	133,60%
50	**5**	**20**	**80000**	**0,2**	**5**	**1**	**3502,6**	**3852,0**	**28,55**	**12,83**	**-16,84**	**26,20**	**31,45**	**44,19**	**9,07%**	**-8,99%**	**59,20%**	**138,11%**
51	5	25	80000	0,3	5	1	6447,5	7094,0	15,51	16,47	18,93	14,23	31,39	44,09	9,11%	-8,98%	47,53%	57,06%
52	**5**	**25**	**80000**	**0,2**	**5**	**1**	**5437,7**	**5981,4**	**18,39**	**15,27**	**2,62**	**16,88**	**31,41**	**44,12**	**9,09%**	**-8,97%**	**51,39%**	**94,06%**
53	5	35	80000	0,3	5	1	8250,8	9080,0	12,12	41,61	67,80	11,12	31,36	44,03	9,13%	-8,96%	-32,69%	-53,98%
54	**5**	**35**	**80000**	**0,2**	**5**	**1**	**7524,5**	**8280,0**	**13,29**	**33,85**	**55,64**	**12,20**	**31,37**	**44,05**	**9,12%**	**-8,97%**	**-7,90%**	**-26,30%**

Row marked with yellow shows the results of reference model for dimensions: B=10m, H=0.5m

Table-3. 20 Analysis results of the beam: B=5m, H=1m, 'c' & '*v*' are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
55	10	30	80000	0,3	5	1	8305,6	9140,0	12,04	42,17	69,38	11,05	31,36	44,03	9,13%	-8,96%	-34,48%	-57,58%
56	10	30	80000	0,2	5	1	7552,9	8310,0	13,24	33,76	56,35	12,15	31,37	44,05	9,11%	-8,95%	-7,61%	-27,91%
57	20	30	80000	0,3	5	1	8569,0	9430,0	11,67	53,88	89,86	10,71	31,35	44,02	9,13%	-8,95%	-71,85%	-104,13%
58	20	30	80000	0,2	5	1	7874,0	8665,0	12,70	49,26	81,81	11,66	31,37	44,04	9,13%	-8,97%	-57,05%	-85,75%
59	50	30	80000	0,3	5	1	8665,5	9536,0	11,54	60,50	99,16	10,59	31,35	44,02	9,13%	-8,95%	-92,98%	-125,27%
60	50	30	80000	0,2	5	1	7974,5	8775,6	12,54	56,02	92,34	11,51	31,36	44,04	9,13%	-8,96%	-78,61%	-109,67%

Table-3. 21 Analysis results of the beam: B=5m, H=1m, 'E' & '*v*' are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
61	5	30	40000	0,3	5	1	3943,2	4336,0	25,36	31,42	52,08	23,27	31,44	44,17	9,06%	-8,97%	0,06%	-17,90%
62	5	30	40000	0,2	5	1	3516,2	3866,4	28,44	21,63	35,81	26,10	31,45	44,19	9,06%	-8,97%	31,22%	18,96%
63	5	30	100000	0,3	5	1	9881,4	10880,0	10,12	30,83	51,04	9,29	31,33	43,98	9,18%	-8,98%	1,59%	-16,06%
64	5	30	100000	0,2	5	1	8802,8	9690,0	11,36	21,30	35,26	10,42	31,35	44,01	9,16%	-8,98%	32,06%	19,89%
65	5	30	150000	0,3	5	1	14836,8	16350,0	6,74	30,39	50,25	6,19	31,24	43,82	9,26%	-8,97%	2,71%	-14,68%
66	5	30	150000	0,2	5	1	13227,5	14576,0	7,56	21,00	34,76	6,94	31,27	43,87	9,25%	-9,00%	32,84%	20,76%
67	5	30	200000	0,3	5	1	19802,0	21840,0	5,05	29,88	49,36	4,64	31,15	43,66	9,33%	-8,95%	4,07%	-13,06%
68	5	30	200000	0,2	5	1	17667,8	19490,0	5,66	20,71	34,28	5,19	31,19	43,73	9,35%	-9,01%	33,59%	21,60%

Table-3. 22 Analysis results of the beam: B=5m, H=0.5m, 'ϕ' & '*v*' are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
69	5	30	80000	0,3	5	0,5	7923,9	7914,8	12,62	26,75	43,85	11,58	27,51	38,36	-0,12%	-8,94%	2,75%	-14,32%
70	5	30	80000	0,2	5	0,5	7082,2	7066,0	14,12	18,39	30,39	12,96	27,60	38,52	-0,23%	-8,93%	33,36%	21,10%
71	5	20	80000	0,3	5	0,5	4175,4	4150,8	23,95	13,76	-13,57	21,98	27,91	39,06	-0,59%	-8,94%	50,69%	134,74%
72	5	20	80000	0,2	5	0,5	3497,7	3474,0	28,59	13,15	-16,06	26,24	27,98	39,19	-0,68%	-8,94%	53,00%	140,98%
73	5	25	80000	0,3	5	0,5	6480,9	6461,4	15,43	16,56	16,72	14,16	27,66	38,63	-0,30%	-8,94%	40,13%	56,72%
74	5	25	80000	0,2	5	0,5	5437,7	5414,0	18,39	15,57	2,93	16,88	27,77	38,82	-0,44%	-8,94%	43,93%	92,45%
75	5	35	80000	0,3	5	0,5	8163,3	8154,0	12,25	34,04	55,06	11,25	27,48	38,31	-0,11%	-8,92%	-23,87%	-43,71%
76	5	35	80000	0,2	5	0,5	7423,9	7416,0	13,47	27,03	44,17	12,36	27,56	38,45	-0,11%	-9,02%	1,92%	-14,87%

Row marked with yellow shows the results of reference model for dimension of beam: B=10m, H=0.5m

Table-3. 23 Analysis results of the beam: B=5m, H=0.5m, 'c' & '*v*' are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
77	10	30	80000	0,3	5	0,5	8223,7	8214,0	12,16	35,62	58,25	11,17	27,48	38,30	-0,12%	-8,90%	-29,65%	-52,07%
78	10	30	80000	0,2	5	0,5	7518,8	7506,0	13,30	29,37	48,67	12,21	27,55	38,43	-0,17%	-8,94%	-6,61%	-26,63%
79	20	30	80000	0,3	5	0,5	8410,4	8404,0	11,89	44,81	73,00	10,92	27,46	38,27	-0,08%	-8,92%	-63,21%	-90,76%
80	20	30	80000	0,2	5	0,5	7758,0	7754,0	12,89	40,36	66,45	11,82	27,52	38,39	-0,05%	-9,03%	-46,64%	-73,10%
81	50	30	80000	0,3	5	0,5	8474,6	8468,0	11,80	49,66	73,11	10,83	27,45	38,26	-0,08%	-8,92%	-80,92%	-91,10%
82	50	30	80000	0,2	5	0,5	7830,9	7826,0	12,77	45,99	73,70	11,71	27,52	38,37	-0,06%	-9,01%	-67,15%	-92,05%

Table-3. 24 Analysis results of the beam: B=5m, H=0.5m, 'E' & '*v*' are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
83	5	30	40000	0,3	5	0,5	3971,4	3946,0	25,18	29,16	48,07	23,12	27,93	39,10	-0,64%	-8,92%	-4,42%	-22,93%
84	5	30	40000	0,2	5	0,5	3548,6	3526,0	28,18	20,44	33,81	25,86	27,97	39,18	-0,64%	-8,98%	26,93%	13,71%
85	5	30	100000	0,3	5	0,5	9891,2	9904,0	10,11	25,64	41,92	9,28	27,30	38,00	0,13%	-8,94%	6,08%	-10,33%
86	5	30	100000	0,2	5	0,5	8833,9	8834,0	11,32	17,41	28,77	10,39	27,41	38,19	0,00%	-8,95%	36,49%	24,67%
87	5	30	150000	0,3	5	0,5	14792,9	14898,0	6,76	23,31	37,89	6,21	26,80	37,12	0,71%	-8,94%	13,03%	-2,09%
88	5	30	150000	0,2	5	0,5	13157,9	13226,0	7,60	15,33	25,33	6,98	26,97	37,41	0,51%	-8,94%	43,15%	32,28%
89	5	30	200000	0,3	5	0,5	19646,4	19896,0	5,09	21,36	34,54	4,67	26,33	36,27	1,25%	-8,92%	18,87%	4,78%
90	5	30	200000	0,2	5	0,5	17699,1	17886,0	5,65	15,05	24,80	5,19	26,52	36,61	1,04%	-8,95%	43,24%	32,25%

Table-3. 25 Analysis results of the beam: B=20m, H=1m, 'ϕ' & '*v*' are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
91	5	30	80000	0,3	20	1	3789,3	4645,0	26,39	58,96	331,96	24,23	76,93	393,11	18,42%	-8,92%	23,36%	15,56%
92	5	30	80000	0,2	20	1	3351,2	4079,0	29,84	44,05	261,99	27,39	79,94	414,09	17,84%	-8,94%	44,90%	36,73%
93	5	20	80000	0,3	20	1	2919,7	3525,0	34,25	17,20	74,54	31,44	83,21	436,90	17,17%	-8,93%	79,33%	82,94%
94	5	20	80000	0,2	20	1	2216,8	2637,0	45,11	17,80	-33,85	41,41	89,26	479,19	15,93%	-8,94%	80,06%	107,06%
95	5	25	80000	0,3	20	1	3703,7	4534,0	27,00	38,42	230,90	24,79	77,50	397,06	18,31%	-8,93%	50,43%	41,85%
96	5	25	80000	0,2	20	1	3076,0	3274,0	32,51	19,28	106,35	29,85	81,99	428,42	6,05%	-8,91%	76,49%	75,18%
97	5	35	80000	0,3	20	1	3803,7	4663,0	26,29	67,22	361,90	24,14	76,84	392,48	18,43%	-8,91%	12,52%	7,79%
98	5	35	80000	0,2	20	1	3385,2	4122,0	29,54	54,66	309,23	27,12	79,70	412,42	17,87%	-8,92%	31,42%	25,02%

Row marked with yellow shows the results of reference model for dimensions: B=10m, H=0.5m

Table-3. 26 Analysis results of the beam: B=20m, H=1m, ‘c’ & ‘v’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
99	10	30	80000	0,3	20	1	3805,2	4667,0	26,28	66,86	361,09	24,12	76,82	392,34	18,47%	-8,96%	12,97%	7,96%
100	**10**	**30**	**80000**	**0,2**	**20**	**1**	**3387,5**	**4125,0**	**29,52**	**53,22**	**307,85**	**27,10**	**79,68**	**412,30**	**17,88%**	**-8,93%**	**33,21%**	**25,33%**
101	20	30	80000	0,3	20	1	3816,8	4680,0	26,20	77,75	392,06	24,06	76,76	391,88	18,44%	-8,91%	-1,29%	-0,05%
102	**20**	**30**	**80000**	**0,2**	**20**	**1**	**3416,5**	**4162,0**	**29,27**	**67,51**	**364,17**	**26,87**	**79,48**	**410,87**	**17,91%**	**-8,92%**	**15,06%**	**11,37%**
103	50	30	80000	0,3	20	1	3821,2	4687,0	26,17	86,76	410,64	24,02	76,72	391,64	18,47%	-8,94%	-13,08%	-4,85%
104	**50**	**30**	**80000**	**0,2**	**20**	**1**	**3427,0**	**4177,0**	**29,18**	**80,68**	**394,36**	**26,78**	**79,40**	**410,30**	**17,96%**	**-8,95%**	**-1,62%**	**3,88%**

Table-3. 27 Analysis results of the beam: B=20m, H=1m, ‘E’ & ‘v’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
105	5	30	40000	0,3	20	1	1932,4	2283,0	51,75	81,57	494,47	47,50	92,02	498,41	15,36%	-8,94%	11,35%	0,79%
106	**5**	**30**	**40000**	**0,2**	**20**	**1**	**1696,4**	**1992,0**	**58,95**	**61,27**	**379,56**	**54,11**	**94,45**	**515,40**	**14,84%**	**-8,94%**	**35,13%**	**26,36%**
107	5	30	100000	0,3	20	1	4710,3	5852,0	21,23	52,41	238,77	19,49	71,44	354,76	19,51%	-8,96%	26,63%	32,69%
108	**5**	**30**	**100000**	**0,2**	**20**	**1**	**4173,6**	**5147,0**	**23,96**	**38,76**	**226,43**	**21,99**	**74,51**	**376,20**	**18,91%**	**-8,95%**	**47,98%**	**39,81%**
109	5	30	150000	0,3	20	1	7002,8	8904,0	14,28	41,94	206,50	13,11	61,35	284,45	21,35%	-8,89%	31,64%	27,40%
110	**5**	**30**	**150000**	**0,2**	**20**	**1**	**6222,8**	**7860,0**	**16,07**	**30,42**	**168,01**	**14,75**	**64,33**	**305,16**	**20,83%**	**-8,93%**	**52,71%**	**44,94%**
111	5	30	200000	0,3	20	1	9293,7	11977,0	10,76	35,70	161,19	9,90	54,54	237,03	22,40%	-8,65%	34,54%	32,00%
112	**5**	**30**	**200000**	**0,2**	**20**	**1**	**8264,5**	**10613,0**	**12,10**	**25,37**	**132,70**	**11,11**	**57,26**	**255,99**	**22,13%**	**-8,95%**	**55,70%**	**48,16%**

Table-3. 28 Analysis results of the beam: B=20m, H=0.5m, ‘ϕ’ & ‘v’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
113	5	30	80000	0,3	20	0,5	3679,2	4467,0	27,18	18,55	55,83	24,95	31,69	92,89	17,64%	-8,92%	41,46%	39,90%
114	**5**	**30**	**80000**	**0,2**	**20**	**0,5**	**3283,0**	**3972,0**	**30,46**	**13,61**	**44,98**	**27,97**	**33,12**	**102,70**	**17,35%**	**-8,92%**	**58,91%**	**56,20%**
115	5	20	80000	0,3	20	0,5	2877,7	3467,0	34,75	16,46	23,30	31,90	34,92	115,03	17,00%	-8,94%	52,86%	79,74%
116	**5**	**20**	**80000**	**0,2**	**20**	**0,5**	**2199,7**	**2623,0**	**45,46**	**15,47**	**20,89**	**41,74**	**39,07**	**143,66**	**16,14%**	**-8,93%**	**60,40%**	**85,46%**
117	5	25	80000	0,3	20	0,5	3633,7	4410,0	27,52	16,17	40,73	25,27	31,84	93,93	17,60%	-8,92%	49,22%	56,64%
118	**5**	**25**	**80000**	**0,2**	**20**	**0,5**	**3042,3**	**3672,0**	**32,87**	**14,71**	**23,78**	**30,18**	**34,14**	**109,69**	**17,15%**	**-8,93%**	**56,92%**	**78,32%**
119	5	35	80000	0,3	20	0,5	3683,2	4472,0	27,15	24,20	61,85	24,93	31,68	92,80	17,64%	-8,92%	23,60%	33,35%
120	**5**	**35**	**80000**	**0,2**	**20**	**0,5**	**3304,7**	**4000,0**	**30,26**	**18,02**	**51,86**	**27,78**	**33,04**	**102,09**	**17,38%**	**-8,94%**	**45,45%**	**49,20%**

Row marked with yellow shows the results of reference model for dimensions: B=10m, H=0.5m

Table-3. 29 Analysis results of the beam: B=20m, H=0.5m, ‘c’ & ‘*v*’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
121	10	30	80000	0,3	20	0,5	3684,6	4474,0	27,14	23,74	61,62	24,92	31,67	92,76	17,64%	-8,93%	25,04%	33,57%
122	10	30	80000	0,2	20	0,5	3308,0	4004,0	30,23	17,51	51,56	27,75	33,02	102,01	17,38%	-8,94%	46,97%	49,45%
123	20	30	80000	0,3	20	0,5	3688,7	4479,0	27,11	31,04	68,96	24,89	31,66	92,68	17,65%	-8,93%	1,95%	25,59%
124	20	30	80000	0,2	20	0,5	3320,1	4019,0	30,12	26,85	61,92	27,65	32,98	101,68	17,39%	-8,94%	18,57%	39,11%
125	50	30	80000	0,3	20	0,5	3690,0	4481,0	27,10	37,32	73,96	24,88	31,65	92,64	17,65%	-8,93%	-17,91%	20,16%
126	50	30	80000	0,2	20	0,5	3325,6	4025,0	30,07	32,60	69,01	27,61	32,96	101,56	17,38%	-8,91%	1,08%	32,05%

Table-3. 30 Analysis results of the beam: B=20m, H=0.5m, ‘E’ & ‘*v*’ are variable

									PLAXIS Analysis Results			SAP2000 Analysis Results						
Model No	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k_s (KN/m³) from PLAXIS	k_s (KN/m³) from SAP2000	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	Spring Constant 'k_s' Deviation % (PLAXIS/SAP)	Settlement Deviation % (PLAXIS/SAP)	V Deviation % (PLAXIS/SAP)	M Deviation % (PLAXIS/SAP)
127	5	30	40000	0,3	20	0,5	1848,1	2187,0	54,11	27,42	104,32	49,68	42,11	164,71	15,50%	-8,92%	34,88%	36,66%
128	5	30	40000	0,2	20	0,5	1647,2	1939,0	60,71	18,69	87,16	55,73	44,26	179,64	15,05%	-8,93%	57,77%	51,48%
129	5	30	100000	0,3	20	0,5	4595,6	5613,0	21,76	16,30	46,05	19,98	29,20	75,94	18,13%	-8,92%	44,17%	39,36%
130	5	30	100000	0,2	20	0,5	4100,0	4993,0	24,39	13,47	36,46	22,39	30,43	84,29	17,88%	-8,92%	55,73%	56,74%
131	5	30	150000	0,3	20	0,5	6887,1	8484,0	14,52	13,02	32,66	13,33	25,57	52,14	18,82%	-8,92%	49,07%	37,36%
132	5	30	150000	0,3	20	0,5	6142,5	7551,0	16,28	13,18	25,03	14,95	26,49	57,93	18,65%	-8,93%	50,24%	56,79%
133	5	30	200000	0,3	20	0,5	9174,3	11353,0	10,90	11,97	25,54	10,01	23,58	40,28	19,19%	-8,92%	49,23%	36,59%
134	5	30	200000	0,2	20	0,5	8190,0	10118,0	12,21	13,07	19,25	11,21	24,31	44,56	19,06%	-8,92%	46,24%	56,80%

The results of obtained from these analyses will be further discussed in Chapter 4.

3.3 Concluding Remarks

In this chapter, software programs used in this study are introduced firstly. Subsequently; material properties, soil properties and foundation member geometry to be modeled are stated. In addition, the first created PLAXIS and SAP2000 models and their comparisons with each other are mentioned. Finally, analysis results for beams with different geometries and soil properties are presented. Furthermore, 134 analyses were done in this study, 2 of them are ignored due to excessive deviation. Modulus of Elasticity ‘E’, internal friction angle of soil ‘ϕ’, cohesion ‘c’, Poisson’s ratio of soil ‘*v*’, width of foundation ‘B’ and thickness of foundation ‘H’ are parameters which utilized in analyses.

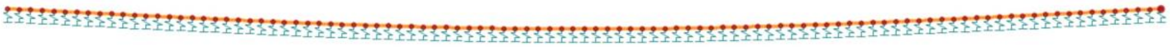
4. DISCUSSION of RESULTS

4.1 Modeling

4.1.1 Modeling in SAP2000

As mentioned in the previous chapter, three zones for subgrade reaction modulus were defined on the beam element in SAP2000 model. The length and spring constants of these zones have been determined according to the results of repetitive analyses. As previously explained, it was observed that SAP2000 analyses conducted without defining zones, deformation shape of beam does not give consistent results and internal forces do not correspond to PLAXIS results as can be examined in Figure-4.1 and Table-4.1;

(a) Deformed shape of beam without spring zones

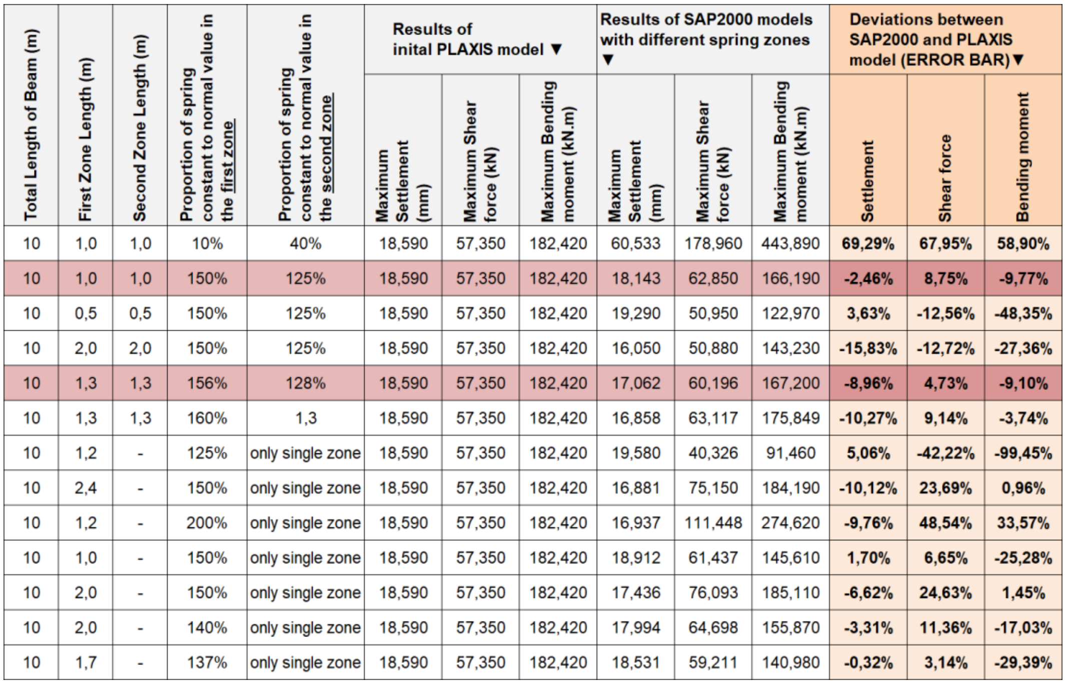


(b) Deformed shape of beam with spring zones

Figure-4. 1 Deformed shapes of the beams with and without spring zones

(Deformed shape of beams scaled up 300 times)

Table-4. 1 Results of SAP2000 models with different spring zones



Total Length of Beam (m)	First Zone Length (m)	Second Zone Length (m)	Proportion of spring constant to normal value in the first zone	Proportion of spring constant to normal value in the second zone	Results of inital PLAXIS model ▼			Results of SAP2000 models with different spring zones ▼			Deviations between SAP2000 and PLAXIS model (ERROR BAR) ▼		
					Maximum Settlement (mm)	Maximum Shear force (kN)	Maximum Bending moment (kN.m)	Maximum Settlement (mm)	Maximum Shear force (kN)	Maximum Bending moment (kN.m)	**Settlement**	**Shear force**	**Bending moment**
10	1,0	1,0	10%	40%	18,590	57,350	182,420	60,533	178,960	443,890	**69,29%**	**67,95%**	**58,90%**
10	1,0	1,0	150%	125%	18,590	57,350	182,420	18,143	62,850	166,190	**-2,46%**	**8,75%**	**-9,77%**
10	0,5	0,5	150%	125%	18,590	57,350	182,420	19,290	50,950	122,970	**3,63%**	**-12,56%**	**-48,35%**
10	2,0	2,0	150%	125%	18,590	57,350	182,420	16,050	50,880	143,230	**-15,83%**	**-12,72%**	**-27,36%**
10	1,3	1,3	156%	128%	18,590	57,350	182,420	17,062	60,196	167,200	**-8,96%**	**4,73%**	**-9,10%**
10	1,3	1,3	160%	1,3	18,590	57,350	182,420	16,858	63,117	175,849	**-10,27%**	**9,14%**	**-3,74%**
10	1,2	-	125%	only single zone	18,590	57,350	182,420	19,580	40,326	91,460	**5,06%**	**-42,22%**	**-99,45%**
10	2,4	-	150%	only single zone	18,590	57,350	182,420	16,881	75,150	184,190	**-10,12%**	**23,69%**	**0,96%**
10	1,2	-	200%	only single zone	18,590	57,350	182,420	16,937	111,448	274,620	**-9,76%**	**48,54%**	**33,57%**
10	1,0	-	150%	only single zone	18,590	57,350	182,420	18,912	61,437	145,610	**1,70%**	**6,65%**	**-25,28%**
10	2,0	-	150%	only single zone	18,590	57,350	182,420	17,436	76,093	185,110	**-6,62%**	**24,63%**	**1,45%**
10	2,0	-	140%	only single zone	18,590	57,350	182,420	17,994	64,698	155,870	**-3,31%**	**11,36%**	**-17,03%**
10	1,7	-	137%	only single zone	18,590	57,350	182,420	18,531	59,211	140,980	**-0,32%**	**3,14%**	**-29,39%**

- Results of initial PLAXIS model given in Figure-3.5 & Figure-3.6
- Rows marked with red show the conditions and results of the most consistent SAP2000 models

As can be seen in the figures and tables above, defining the spring zones with different stiffness properties at the edges of beam provides more consistent and accurate results. Therefore, it is recommended that spring zones should be defined at the edges of the beam. In this study, model whose length of the first and the second zone is 13% of total length of beam (model in fifth row at Table-4.1) has been preferred due to smaller deviations. Spring constant of the first and the second zones are 1.56 and 1.28 times of the middle zone respectively. Illustration of recommended spring zones can be examined in Figure-4.2;

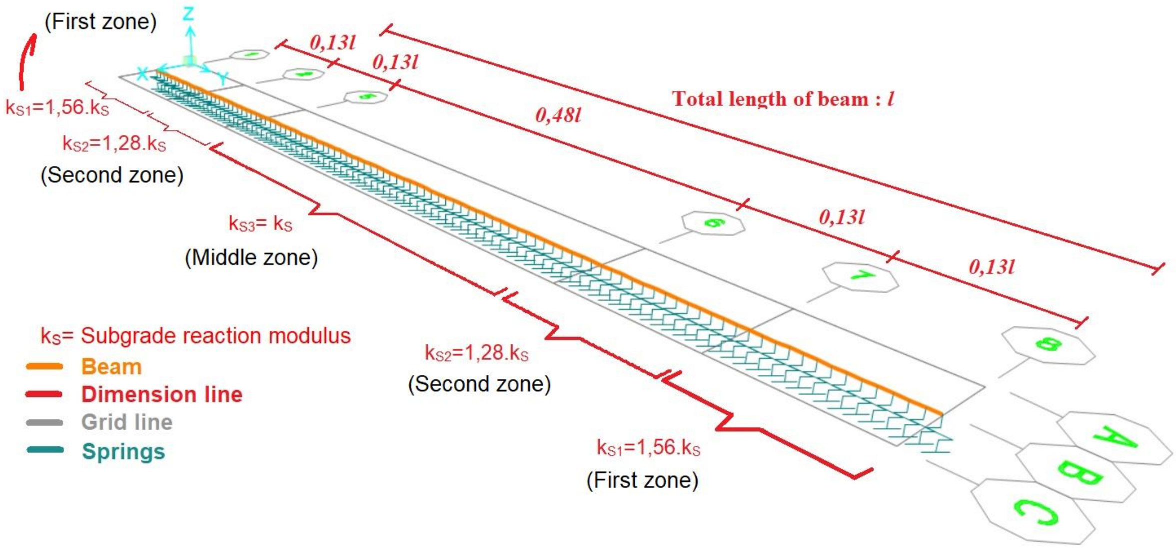


Figure-4. 2 Zones with different subgrade reaction modulus (spring constant)

4.1.2 Modeling in PLAXIS

While modeling any type of geotechnical structure or soil in PLAXIS, they are divided into finite number of meshes. In general, defining finer meshes in finite element method, more realistic solutions can be obtained. Keeping all other parameters constant, results obtained from very coarse and medium mesh sizes are presented in Figure-4.3 through Figure-4.6;

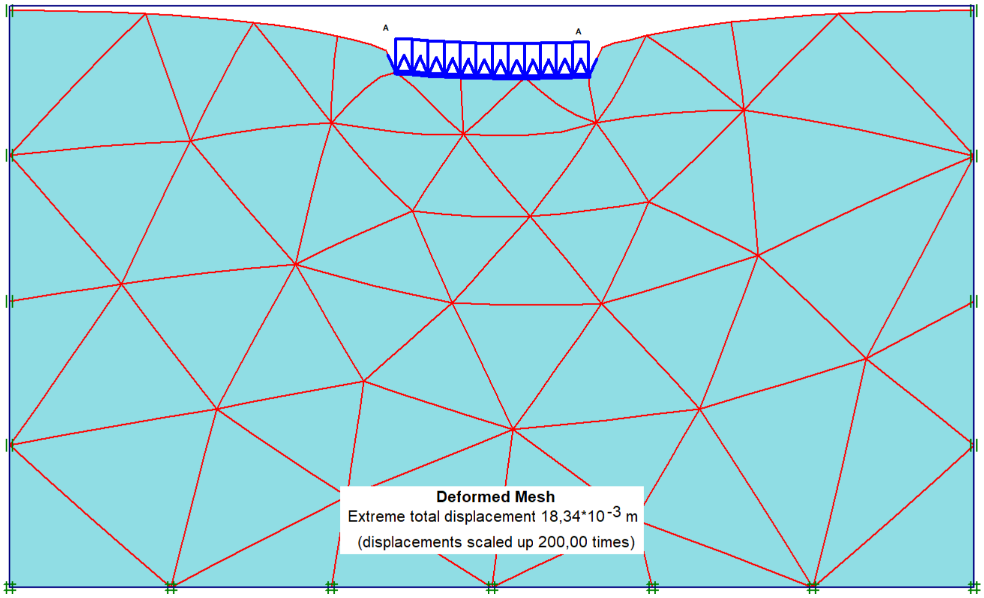
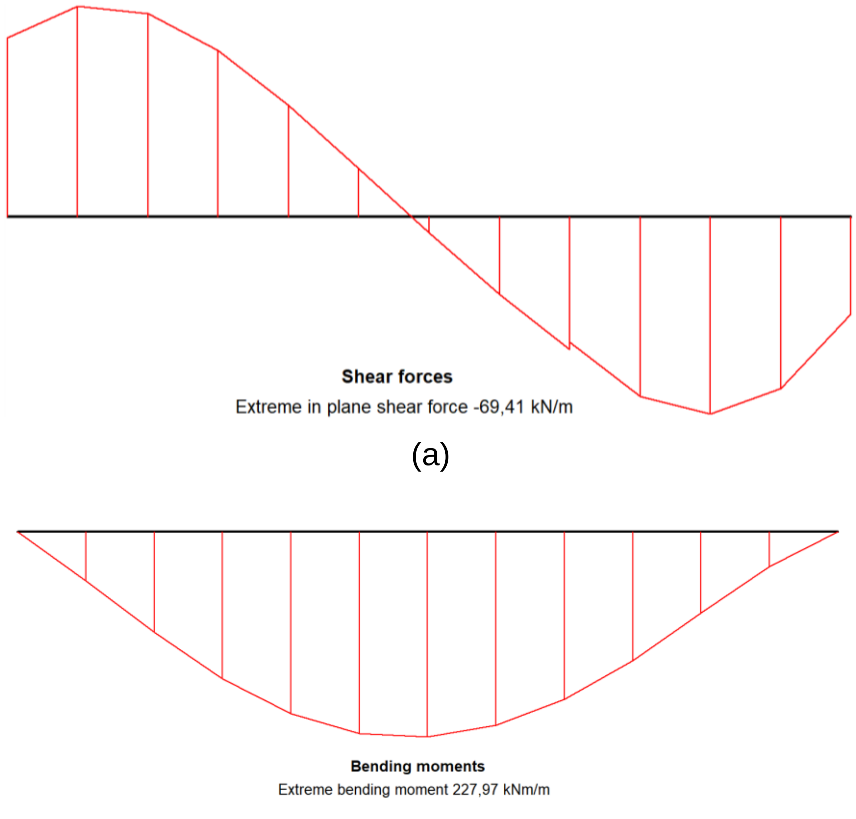


Figure-4. 3 Deformed shape of very coarse-grained soil medium



(b)

Figure-4. 4 Maximum internal forces (very coarse-grained model)

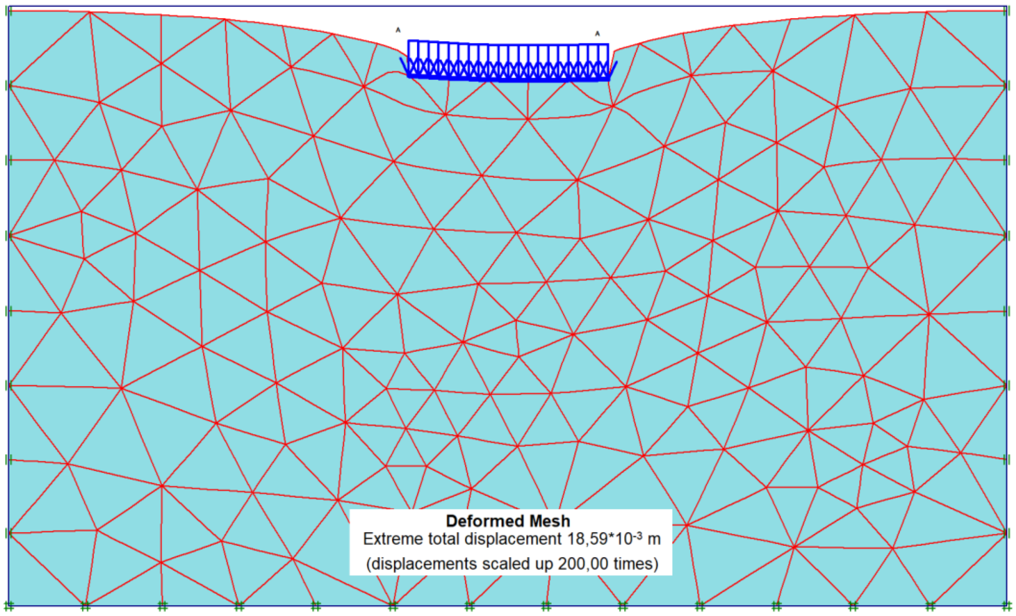
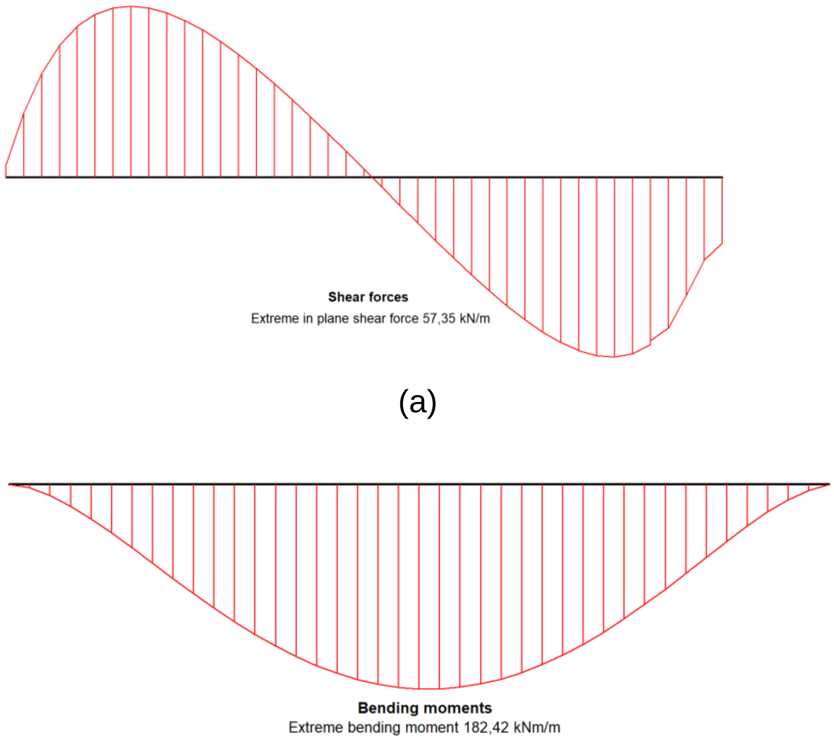


Figure-4. 5 Deformed shape of medium grained soil medium



(a)

(b)

Figure-4. 6 Maximum internal forces in beam section (medium-grained model)

As can be seen in foregoing figures, although settlement values do not vary too much, internal forces of plate (beam, foundation etc.) vary 20% ~ 25% approximately. In case internal forces have been assumed as reference, this situation may lead to mistakes. Consequently, dividing the soil into as much mesh as possible will give more realistic results. However, it should be remembered that the analyses will be more laborious and time consuming.

4.2 Parameters Which Affect the Results

4.2.1 Internal Friction Angle ‘ϕ’

The internal friction angle is one of the most critical parameters in terms of shear strength of the soil. It is a parameter that mostly represents granular soils such as sands and gravels. Angle of internal friction is represented by the slope of failure envelope in Mohr-Coulomb failure criterion graph as can be examined in Figure-4.7;

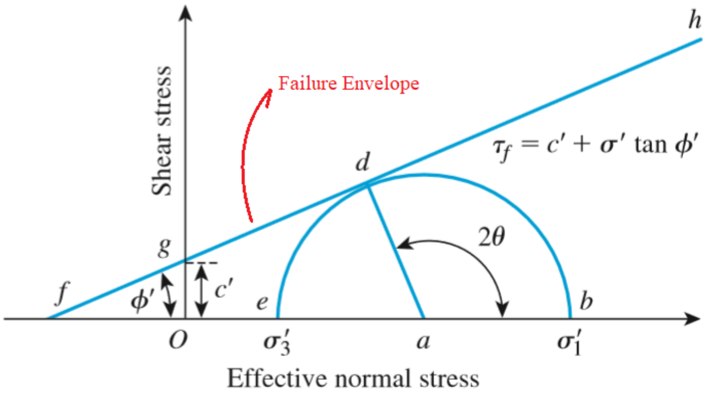


Figure-4. 7 Mohr's circle and failure envelope

According to the results of the analyses, it is observed that the maximum settlement of the foundation member decreases significantly as the internal friction angle increases. Compared to the reference model, variation of the settlement value reaches up to 80-90% level. For the foundations of different geometry, the analysis results according to the cases where the Poisson's ratio equals to the 0.2 and 0.3 are presented in Table-4.2 through Table-4.7. Since effect of internal friction angle on spring constant is examined in only PLAXIS software in this chapter, only spring constant obtained from PLAXIS has been presented in tables below.

Table-4. 2 Variation of settlement value if ϕ is variable, v=0.3 and B=10m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	v	B (m)	H (m)	k (KN/m^3) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
Ø variable	**5**	**30**	**80000**	**0.3**	**10**	**1.0**	**5379.2**	**18.59**	**57.35**	**182.42**	**Reference model**	**Reference model**
	5	20	80000	0.3	10	1.0	**3238.3**	30.88	13.15	-16.03	66.11%	-39.80%
	5	25	80000	0.3	10	1.0	**4863.8**	20.56	33.46	112.44	10.60%	-9.58%
	5	35	80000	0.3	10	1.0	**5500.6**	18.18	72.78	231.37	-2.21%	2.26%
Ø variable	**5**	**30**	**80000**	**0.3**	**10**	**0.5**	**5216.5**	**19.17**	**28.26**	**82.29**	**Reference model**	**Reference model**
	5	20	80000	0.3	10	0.5	**3219.6**	31.06	12.08	-10.65	62.02%	-38.28%
	5	25	80000	0.3	10	0.5	**4710.3**	21.23	19.68	46.84	10.75%	-9.70%
	5	35	80000	0.3	10	0.5	**5271.5**	18.97	35.33	97.00	-1.04%	1.05%

Table-4. 3 Variation of settlement value if ϕ is variable, ν=0.3 and B=5m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
Ø variable	**5**	**30**	**80000**	**0.3**	**5**	**1.0**	**7898.9**	**12.66**	**31.02**	**51.38**	**Reference model**	**Reference model**
	5	20	80000	0.3	5	1.0	4180.6	23.92	13.93	-14.84	88.94%	-47.07%
	5	25	80000	0.3	5	1.0	6447.5	15.51	16.47	18.93	22.51%	-18.38%
	5	35	80000	0.3	5	1.0	8250.8	12.12	41.61	67.80	-4.27%	4.46%
Ø variable	**5**	**30**	**80000**	**0.3**	**5**	**0.5**	**7923.9**	**12.62**	**26.75**	**43.85**	**Reference model**	**Reference model**
	5	20	80000	0.3	5	0.5	4175.4	23.95	13.76	-13.57	89.78%	-47.31%
	5	25	80000	0.3	5	0.5	6480.9	15.43	16.56	16.72	22.27%	-18.21%
	5	35	80000	0.3	5	0.5	8163.3	12.25	34.04	55.06	-2.93%	3.02%

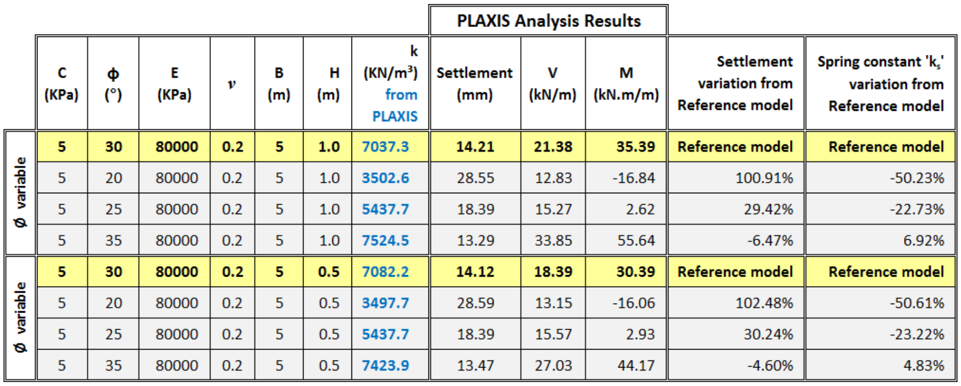
Table-4. 4 Variation of settlement value if ϕ is variable, ν =0.3 and B=20m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
Ø variable	**5**	**30**	**80000**	**0.3**	**20**	**1.0**	**3789.3**	**26.39**	**58.96**	**331.96**	**Reference model**	**Reference model**
	5	20	80000	0.3	20	1.0	2919.7	34.25	17.20	74.54	29.78%	-22.95%
	5	25	80000	0.3	20	1.0	3703.7	27.00	38.42	230.90	2.31%	-2.26%
	5	35	80000	0.3	20	1.0	3803.7	26.29	67.22	361.90	-0.38%	0.38%
Ø variable	**5**	**30**	**80000**	**0.3**	**20**	**0.5**	**3679.2**	**27.18**	**18.55**	**55.83**	**Reference model**	**-2.91%**
	5	20	80000	0.3	20	0.5	2877.7	34.75	16.46	23.30	27.85%	-24.06%
	5	25	80000	0.3	20	0.5	3633.7	27.52	16.17	40.73	1.25%	-4.11%
	5	35	80000	0.3	20	0.5	3683.2	27.15	24.20	61.85	-0.11%	-2.80%

Table-4. 5 Variation of settlement value if ϕ is variable, ν=0.2 and B=10m

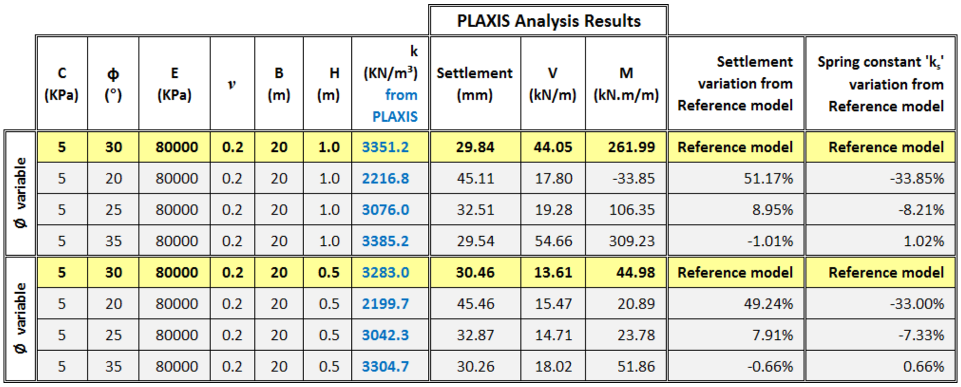
								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
Ø variable	**5**	**30**	**80000**	**0.2**	**10**	**1.0**	**4775.5**	**20.94**	**41.19**	**131.44**	**Reference model**	**Reference model**
	5	20	80000	0.2	10	1.0	2613.7	38.26	18.68	-41.60	82.71%	-45.27%
	5	25	80000	0.2	10	1.0	3824.1	26.15	16.51	25.45	24.88%	-19.92%
	5	35	80000	0.2	10	1.0	4928.5	20.29	57.95	185.65	-3.10%	3.20%
Ø variable	**5**	**30**	**80000**	**0.2**	**10**	**0.5**	**4694.8**	**21.30**	**20.33**	**61.81**	**Reference model**	**Reference model**
	5	20	80000	0.2	10	0.5	2576.0	38.82	13.75	-20.76	82.25%	-45.13%
	5	25	80000	0.2	10	0.5	3849.1	25.98	16.11	15.46	21.97%	-18.01%
	5	35	80000	0.2	10	0.5	4812.3	20.78	29.01	83.39	-2.44%	2.50%

Table-4. 6 Variation of settlement value if ϕ is variable, ν=0.2 and B=5m



								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m^3) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
ϕ variable	**5**	**30**	**80000**	**0.2**	**5**	**1.0**	**7037.3**	**14.21**	**21.38**	**35.39**	**Reference model**	**Reference model**
	5	20	80000	0.2	5	1.0	3502.6	28.55	12.83	-16.84	100.91%	-50.23%
	5	25	80000	0.2	5	1.0	5437.7	18.39	15.27	2.62	29.42%	-22.73%
	5	35	80000	0.2	5	1.0	7524.5	13.29	33.85	55.64	-6.47%	6.92%
ϕ variable	**5**	**30**	**80000**	**0.2**	**5**	**0.5**	**7082.2**	**14.12**	**18.39**	**30.39**	**Reference model**	**Reference model**
	5	20	80000	0.2	5	0.5	3497.7	28.59	13.15	-16.06	102.48%	-50.61%
	5	25	80000	0.2	5	0.5	5437.7	18.39	15.57	2.93	30.24%	-23.22%
	5	35	80000	0.2	5	0.5	7423.9	13.47	27.03	44.17	-4.60%	4.83%

Table-4. 7 Variation of settlement value if ϕ is variable, ν=0.2 and B=20m



								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m^3) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
ϕ variable	**5**	**30**	**80000**	**0.2**	**20**	**1.0**	**3351.2**	**29.84**	**44.05**	**261.99**	**Reference model**	**Reference model**
	5	20	80000	0.2	20	1.0	2216.8	45.11	17.80	-33.85	51.17%	-33.85%
	5	25	80000	0.2	20	1.0	3076.0	32.51	19.28	106.35	8.95%	-8.21%
	5	35	80000	0.2	20	1.0	3385.2	29.54	54.66	309.23	-1.01%	1.02%
ϕ variable	**5**	**30**	**80000**	**0.2**	**20**	**0.5**	**3283.0**	**30.46**	**13.61**	**44.98**	**Reference model**	**Reference model**
	5	20	80000	0.2	20	0.5	2199.7	45.46	15.47	20.89	49.24%	-33.00%
	5	25	80000	0.2	20	0.5	3042.3	32.87	14.71	23.78	7.91%	-7.33%
	5	35	80000	0.2	20	0.5	3304.7	30.26	18.02	51.86	-0.66%	0.66%

Variation of settlement with respect to 'ϕ', ν is also given in Figure-4.8 and Figure-4.9. These figures summarize the findings presented in the tables above. Some of the bending moment values in tables above are seemed with minus ' - ' sign. It has been observed that decreasing the internal friction angle to a specific value (this value is ϕ=20° in performed analyses) causes the moment diagram to change direction.

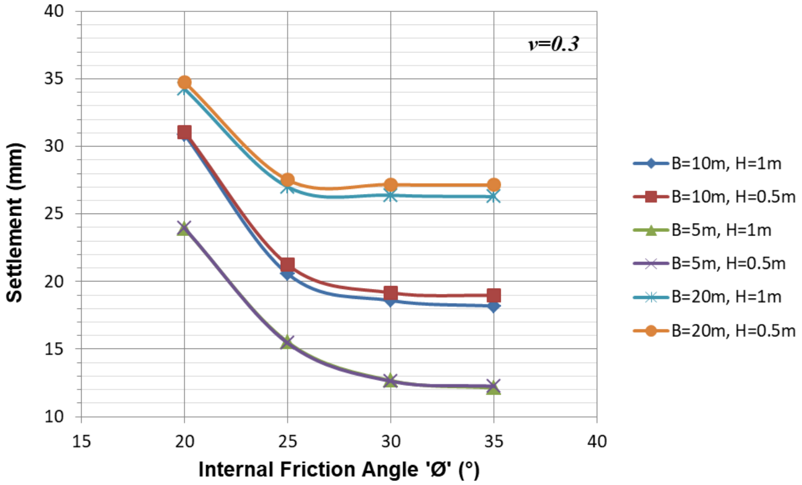


Figure-4. 8 ‘ϕ’ – Settlement variation for v=0.3

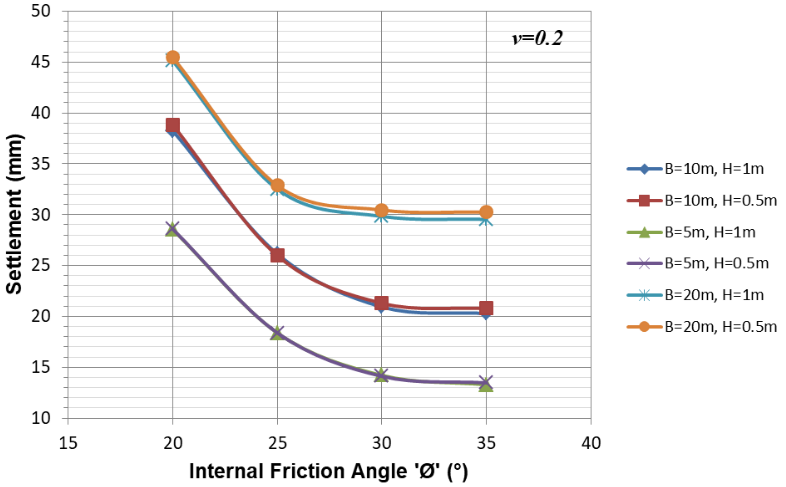


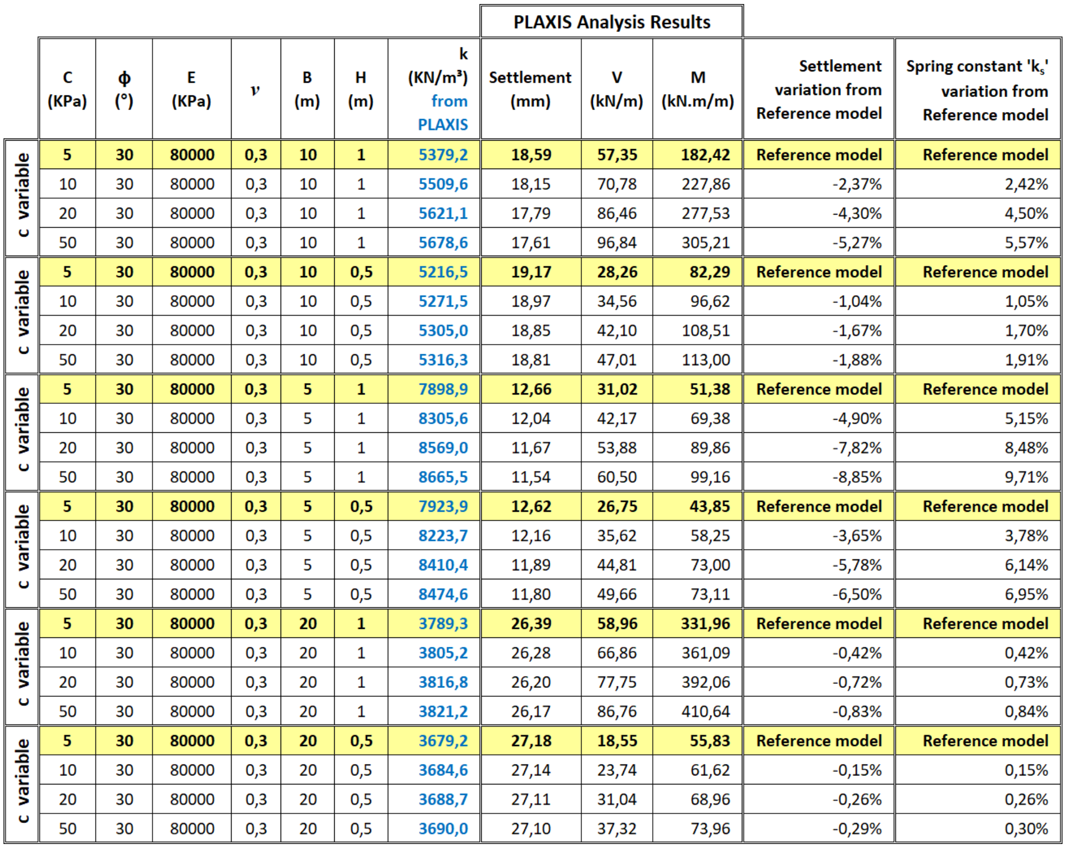
Figure-4. 9 ‘ϕ’ – Settlement variation for v=0.2

As can be seen in tables and figures above, internal friction angle ‘ϕ’ affects the settlement values considerably. It can be concluded that ‘ϕ’ can be used as parameter that to determine the subgrade reaction modulus ‘k_S’.

4.2.2 Cohesion ‘c’

The other shear strength parameter that was used in this study is cohesion ‘c’. It is a parameter that mostly represents cohesive soils such as silts and clays. Cohesion is represented by vertical axis in Mohr-Coulomb failure criterion chart as showed previously (Figure-4.7). For different geometries and different Poisson’s ratios (ν=0.2 and ν=0.3), analysis results of conditions where cohesion is a variable parameter are submitted in Table-4.8 and Table-4.9. Since effect of cohesion on spring constant is examined in only PLAXIS software in this chapter, only spring constant obtained from PLAXIS has been presented in tables below.

Table-4. 8 Variation of settlement value if c is variable and ν=0.3



								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
c variable	**5**	**30**	**80000**	**0,3**	**10**	**1**	**5379,2**	**18,59**	**57,35**	**182,42**	**Reference model**	**Reference model**
	10	30	80000	0,3	10	1	5509,6	18,15	70,78	227,86	-2,37%	2,42%
	20	30	80000	0,3	10	1	5621,1	17,79	86,46	277,53	-4,30%	4,50%
	50	30	80000	0,3	10	1	5678,6	17,61	96,84	305,21	-5,27%	5,57%
c variable	**5**	**30**	**80000**	**0,3**	**10**	**0,5**	**5216,5**	**19,17**	**28,26**	**82,29**	**Reference model**	**Reference model**
	10	30	80000	0,3	10	0,5	5271,5	18,97	34,56	96,62	-1,04%	1,05%
	20	30	80000	0,3	10	0,5	5305,0	18,85	42,10	108,51	-1,67%	1,70%
	50	30	80000	0,3	10	0,5	5316,3	18,81	47,01	113,00	-1,88%	1,91%
c variable	**5**	**30**	**80000**	**0,3**	**5**	**1**	**7898,9**	**12,66**	**31,02**	**51,38**	**Reference model**	**Reference model**
	10	30	80000	0,3	5	1	8305,6	12,04	42,17	69,38	-4,90%	5,15%
	20	30	80000	0,3	5	1	8569,0	11,67	53,88	89,86	-7,82%	8,48%
	50	30	80000	0,3	5	1	8665,5	11,54	60,50	99,16	-8,85%	9,71%
c variable	**5**	**30**	**80000**	**0,3**	**5**	**0,5**	**7923,9**	**12,62**	**26,75**	**43,85**	**Reference model**	**Reference model**
	10	30	80000	0,3	5	0,5	8223,7	12,16	35,62	58,25	-3,65%	3,78%
	20	30	80000	0,3	5	0,5	8410,4	11,89	44,81	73,00	-5,78%	6,14%
	50	30	80000	0,3	5	0,5	8474,6	11,80	49,66	73,11	-6,50%	6,95%
c variable	**5**	**30**	**80000**	**0,3**	**20**	**1**	**3789,3**	**26,39**	**58,96**	**331,96**	**Reference model**	**Reference model**
	10	30	80000	0,3	20	1	3805,2	26,28	66,86	361,09	-0,42%	0,42%
	20	30	80000	0,3	20	1	3816,8	26,20	77,75	392,06	-0,72%	0,73%
	50	30	80000	0,3	20	1	3821,2	26,17	86,76	410,64	-0,83%	0,84%
c variable	**5**	**30**	**80000**	**0,3**	**20**	**0,5**	**3679,2**	**27,18**	**18,55**	**55,83**	**Reference model**	**Reference model**
	10	30	80000	0,3	20	0,5	3684,6	27,14	23,74	61,62	-0,15%	0,15%
	20	30	80000	0,3	20	0,5	3688,7	27,11	31,04	68,96	-0,26%	0,26%
	50	30	80000	0,3	20	0,5	3690,0	27,10	37,32	73,96	-0,29%	0,30%

Table-4. 9 Variation of settlement value if c is variable and ν=0.2

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
c variable	**5**	**30**	**80000**	**0,2**	**10**	**1**	**4775,5**	**20,94**	**41,19**	**131,44**	**Reference model**	**Reference model**
	10	30	80000	0,2	10	1	4945,6	20,22	56,60	183,34	-3,44%	3,56%
	20	30	80000	0,2	10	1	5096,8	19,62	76,62	248,29	-6,30%	6,73%
	50	30	80000	0,2	10	1	5168,0	19,35	89,94	284,79	-7,59%	8,22%
c variable	**5**	**30**	**80000**	**0,2**	**10**	**0,5**	**4694,8**	**21,30**	**20,33**	**61,81**	**Reference model**	**Reference model**
	10	30	80000	0,2	10	0,5	4805,4	20,81	27,52	81,41	-2,30%	2,35%
	20	30	80000	0,2	10	0,5	4870,9	20,53	37,12	100,02	-3,62%	3,75%
	50	30	80000	0,2	10	0,5	4890,0	20,45	42,50	106,48	-3,99%	4,16%
c variable	**5**	**30**	**80000**	**0,2**	**5**	**1**	**7037,3**	**14,21**	**21,38**	**35,39**	**Reference model**	**Reference model**
	10	30	80000	0,2	5	1	7552,9	13,24	33,76	56,35	-6,83%	7,33%
	20	30	80000	0,2	5	1	7874,0	12,70	49,26	81,81	-10,63%	11,89%
	50	30	80000	0,2	5	1	7974,5	12,54	56,02	92,34	-11,75%	13,32%
c variable	**5**	**30**	**80000**	**0,2**	**5**	**0,5**	**7082,2**	**14,12**	**18,39**	**30,39**	**Reference model**	**Reference model**
	10	30	80000	0,2	5	0,5	7518,8	13,30	29,37	48,67	-5,81%	6,17%
	20	30	80000	0,2	5	0,5	7758,0	12,89	40,36	66,45	-8,71%	9,54%
	50	30	80000	0,2	5	0,5	7830,9	12,77	45,99	73,70	-9,56%	10,57%
c variable	**5**	**30**	**80000**	**0,2**	**20**	**1**	**3351,2**	**29,84**	**44,05**	**261,99**	**Reference model**	**Reference model**
	10	30	80000	0,2	20	1	3387,5	29,52	53,22	307,85	-1,07%	1,08%
	20	30	80000	0,2	20	1	3416,5	29,27	67,51	364,17	-1,91%	1,95%
	50	30	80000	0,2	20	1	3427,0	29,18	80,68	394,36	-2,21%	2,26%
c variable	**5**	**30**	**80000**	**0,2**	**20**	**0,5**	**3283,0**	**30,46**	**13,61**	**44,98**	**Reference model**	**Reference model**
	10	30	80000	0,2	20	0,5	3308,0	30,23	17,51	51,56	-0,76%	0,76%
	20	30	80000	0,2	20	0,5	3320,1	30,12	26,85	61,92	-1,12%	1,13%
	50	30	80000	0,2	20	0,5	3325,6	30,07	32,60	69,01	-1,28%	1,30%

A graphical representation which shows the variation of settlement values with respect to cohesion is given in Figure-4.10 and Figure-4.11 as follows.

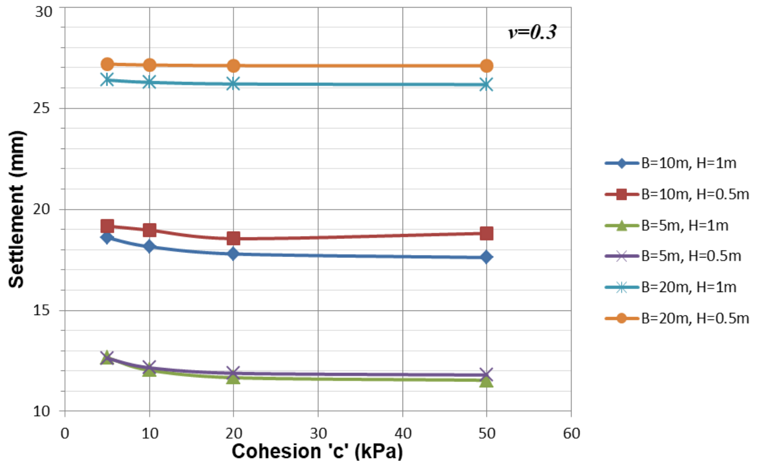


Figure-4. 10 Cohesion – Settlement variation for ν=0.3

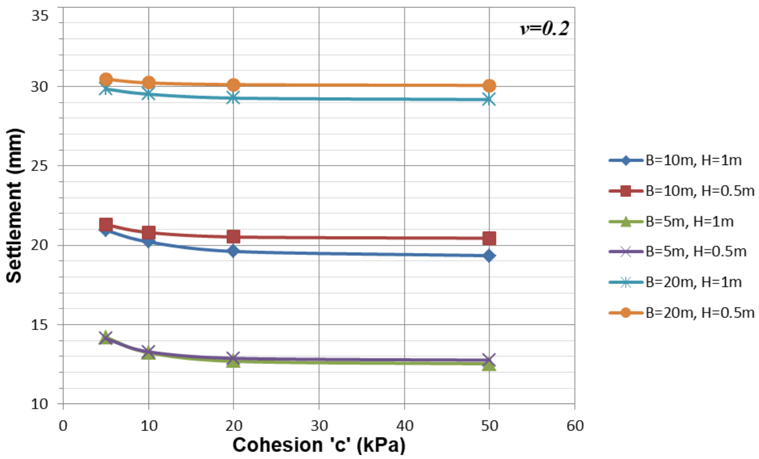


Figure-4. 11 Cohesion – Settlement variation for v=0.2

As can be seen in the previous tables, changing the cohesion value does not affect the results considerably. Considering this fact, cohesion value has not been included in the equation proposed as can be seen in following sections.

4.2.3 Modulus of Elasticity 'E' (Young's modulus)

The most important soil parameter that defines the rigidity of soil is the modulus of elasticity 'E'. This parameter is similar to the spring constant with this aspect. Modulus of elasticity is an indicator of a material's stiffness or resistance to elastic deformation under loading. It is related with stress to strain along an axis or line. The basic principle is that, a material is exposed to elastic deformation when it is compressed or extended and returns to its original shape when the load is removed. More deformation occurs in an elastic material compared to a stiff material. In other words, a low modulus of elasticity value means solid is elastic; a high modulus of elasticity value means a solid is stiff. If we take a glance at Hooke's law and his stress-strain chart, we see that Modulus of elasticity (Young's modulus) of any material have resemblance to the spring constant. Therefore, it can be expected that modulus of elasticity affects the settlement value considerably. The results of the analysis where modulus of elasticity is variable have been presented in Table-4.10 through Table-4.15. Since effect of modulus of elasticity on spring constant is examined in only PLAXIS software in this chapter, only spring constant obtained from PLAXIS has been presented in tables below.

Table-4. 10 Variation of settlement value if E is variable, ν=0.3 and B=10m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
E variable	5	30	40000	0,3	10	1	2699,8	37,04	62,12	198,62	99,25%	-49,81%
	5	30	80000	0,3	10	1	5379,2	18,59	57,35	182,42	Reference model	Reference model
	5	30	100000	0,3	10	1	6706,9	14,91	55,14	174,90	-19,80%	24,68%
	5	30	150000	0,3	10	1	10000,0	10,00	50,35	158,64	-46,21%	85,90%
	5	30	200000	0,3	10	1	13315,6	7,51	48,58	152,71	-59,60%	147,54%
E variable	5	30	40000	0,3	10	0,5	2638,5	37,90	39,19	120,63	97,70%	-49,42%
	5	30	80000	0,3	10	0,5	5216,5	19,17	28,26	82,29	Reference model	Reference model
	5	30	100000	0,3	10	0,5	6497,7	15,39	25,09	70,67	-19,72%	24,56%
	5	30	150000	0,3	10	0,5	9689,9	10,32	19,83	51,86	-46,17%	85,76%
	5	30	200000	0,3	10	0,5	12870,0	7,77	16,95	40,70	-59,47%	146,72%

Table-4. 11 Variation of settlement value if E is variable, ν=0.3 and B=5m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
E variable	5	30	40000	0,3	5	1	3943,2	25,36	31,42	52,08	100,32%	-50,08%
	5	30	80000	0,3	5	1	7898,9	12,66	31,02	51,38	Reference model	Reference model
	5	30	100000	0,3	5	1	9881,4	10,12	30,83	51,04	-20,06%	25,10%
	5	30	150000	0,3	5	1	14836,8	6,74	30,39	50,25	-46,76%	87,83%
	5	30	200000	0,3	5	1	19802,0	5,05	29,88	49,36	-60,11%	150,69%
E variable	5	30	40000	0,3	5	0,5	3971,4	25,18	29,16	48,07	99,52%	-49,88%
	5	30	80000	0,3	5	0,5	7923,9	12,62	26,75	43,85	Reference model	Reference model
	5	30	100000	0,3	5	0,5	9891,2	10,11	25,64	41,92	-19,89%	24,83%
	5	30	150000	0,3	5	0,5	14792,9	6,76	23,31	37,89	-46,43%	86,69%
	5	30	200000	0,3	5	0,5	19646,4	5,09	21,36	34,54	-59,67%	147,94%

Table-4. 12 Variation of settlement value if E is variable, ν=0.3 and B=20m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
E variable	5	30	40000	0,3	20	1	1932,4	51,75	81,57	494,47	96,10%	-49,00%
	5	30	80000	0,3	20	1	3789,3	26,39	58,96	331,96	Reference model	Reference model
	5	30	100000	0,3	20	1	4710,3	21,23	52,41	238,77	-19,55%	24,31%
	5	30	150000	0,3	20	1	7002,8	14,28	41,94	206,50	-45,89%	84,80%
	5	30	200000	0,3	20	1	9293,7	10,76	35,70	161,19	-59,23%	145,26%
E variable	5	30	40000	0,3	20	0,5	1848,1	54,11	27,42	104,32	99,08%	-49,77%
	5	30	80000	0,3	20	0,5	3679,2	27,18	18,55	55,83	Reference model	Reference model
	5	30	100000	0,3	20	0,5	4595,6	21,76	16,30	46,05	-19,94%	24,91%
	5	30	150000	0,3	20	0,5	6887,1	14,52	13,02	32,66	-46,58%	87,19%
	5	30	200000	0,3	20	0,5	9174,3	10,90	11,97	25,54	-59,90%	149,36%

Table-4. 13 Variation of settlement value if E is variable, ν=0.2 and B=10m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k$_s$' variation from Reference model
E variable	5	30	40000	0,2	10	1	2390,6	41,83	44,87	143,46	99,76%	-49,94%
	5	30	80000	0,2	10	1	4775,5	20,94	41,19	131,44	Reference model	Reference model
	5	30	100000	0,2	10	1	5963,0	16,77	39,67	126,47	-19,91%	24,87%
	5	30	150000	0,2	10	1	8920,6	11,21	36,32	115,50	-46,47%	86,80%
	5	30	200000	0,2	10	1	11876,5	8,42	33,60	106,63	-59,79%	148,69%
E variable	5	30	40000	0,2	10	0,5	2364,1	42,30	28,38	89,01	98,59%	-49,65%
	5	30	80000	0,2	10	0,5	4694,8	21,30	20,33	61,81	Reference model	Reference model
	5	30	100000	0,2	10	0,5	5858,2	17,07	18,06	53,58	-19,86%	24,78%
	5	30	150000	0,2	10	0,5	8748,9	11,43	16,42	39,71	-46,34%	86,35%
	5	30	200000	0,2	10	0,5	11641,4	8,59	16,20	31,51	-59,67%	147,96%

Table-4. 14 Variation of settlement value if E is variable, ν=0.2 and B=5m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k$_s$' variation from Reference model
E variable	5	30	40000	0,2	5	1	3516,2	28,44	21,63	35,81	100,14%	-50,04%
	5	30	80000	0,2	5	1	7037,3	14,21	21,38	35,39	Reference model	Reference model
	5	30	100000	0,2	5	1	8802,8	11,36	21,30	35,26	-20,06%	25,09%
	5	30	150000	0,2	5	1	13227,5	7,56	21,00	34,76	-46,80%	87,96%
	5	30	200000	0,2	5	1	17667,8	5,66	20,71	34,28	-60,17%	151,06%
E variable	5	30	40000	0,2	5	0,5	3548,6	28,18	20,44	33,81	99,58%	-49,89%
	5	30	80000	0,2	5	0,5	7082,2	14,12	18,39	30,39	Reference model	Reference model
	5	30	100000	0,2	5	0,5	8833,9	11,32	17,41	28,77	-19,83%	24,73%
	5	30	150000	0,2	5	0,5	13157,9	7,60	15,33	25,33	-46,18%	85,79%
	5	30	200000	0,2	5	0,5	17699,1	5,65	15,05	24,80	-59,99%	149,91%

Table-4. 15 Variation of settlement value if E is variable, ν=0.2 and B=20m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k$_s$' variation from Reference model
E variable	5	30	40000	0,2	20	1	1696,4	58,95	61,27	379,56	97,55%	-49,38%
	5	30	80000	0,2	20	1	3351,2	29,84	44,05	261,99	Reference model	Reference model
	5	30	100000	0,2	20	1	4173,6	23,96	38,76	226,43	-19,71%	24,54%
	5	30	150000	0,2	20	1	6222,8	16,07	30,42	168,01	-46,15%	85,69%
	5	30	200000	0,2	20	1	8264,5	12,10	25,37	132,70	-59,45%	146,61%
E variable	5	30	40000	0,2	20	0,5	1647,2	60,71	18,69	87,16	99,31%	-49,83%
	5	30	80000	0,2	20	0,5	3283,0	30,46	13,61	44,98	Reference model	Reference model
	5	30	100000	0,2	20	0,5	4100,0	24,39	13,47	36,46	-19,93%	24,89%
	5	30	150000	0,2	20	0,5	6142,5	16,28	13,18	25,03	-46,55%	87,10%
	5	30	200000	0,2	20	0,5	8190,0	12,21	13,07	19,25	-59,91%	149,47%

Modulus of elasticity and settlement variation is given in Figure-4.12 and Figure-4.13.

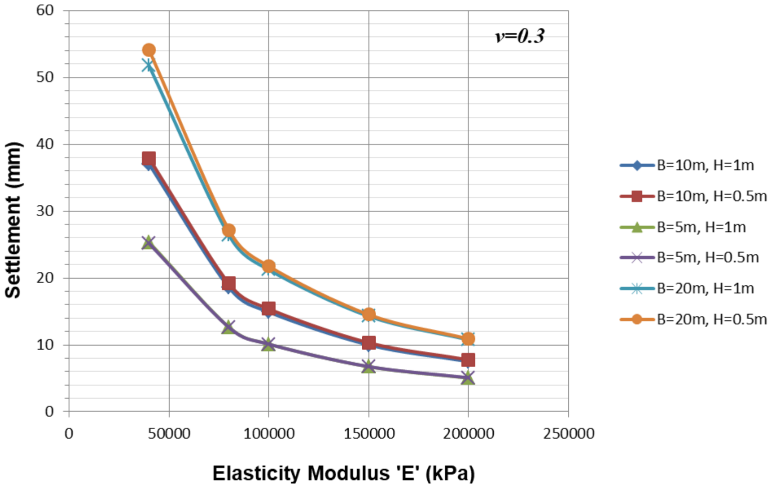


Figure-4. 12 Modulus of elasticity – settlement variation for ν=0.3

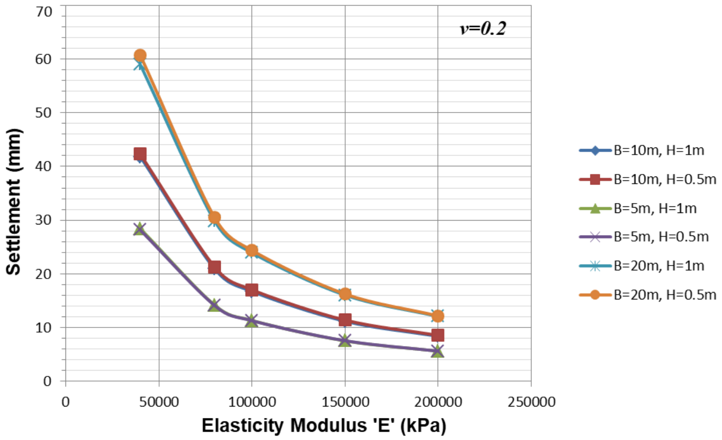
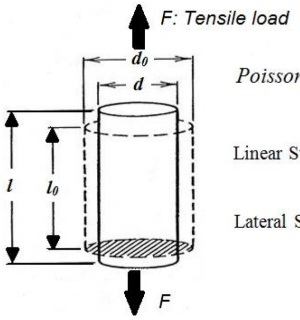


Figure-4. 13 Modulus of elasticity – settlement variation for ν=0.2

As can be seen in tables and figures above, there is a directly relationship between settlement and modulus of elasticity. It has been observed that Modulus of elasticity increases, settlement values decrease. Considering these conditions, using modulus of elasticity in equation to be proposed is highly recommended.

4.2.4 Poisson's Ratio '*v*'

Poisson's ratio defines the lateral deformation of any material under loading at axis perpendicular to the lateral axis. This parameter is significant for elastic properties and used for studying on load and deflection characteristics and effective for isotropic materials. Poisson's Ratio is described as can be examined in Figure-4.14;



$$\text{Poisson's ratio 'v'} = \frac{\text{Lateral Strain}}{\text{Linear Strain}}$$

$$\text{Linear Strain} = \frac{\Delta l}{l} = \frac{l - l_0}{l_0}$$

$$\text{Lateral Strain} = \frac{\Delta d}{d_0} = \frac{d - d_0}{d_0}$$

Figure-4. 14 Illustration of Poisson's ratio definition

All analysis results for Poisson's ratio of ' $v = 0.3$ ' and ' $v = 0.2$ ' have been submitted in Table-4.16 through Table-4.18. Since effect of Poisson's Ratio on spring constant is examined in only PLAXIS software in this chapter, only spring constant obtained from PLAXIS has been presented in tables below.

Table-4. 16 Analysis results for beam: B=10m and H=1m & 0.5m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m^3) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k_s' variation from Reference model
Ø - ν variable	5	30	80000	0.3	10	1	5379.2	18.59	57.35	182.42	Reference model	Reference model
	5	30	80000	0.2	10	1	4775.5	20.94	41.19	131.44	12.64%	-11.22%
	5	20	80000	0.3	10	1	3238.3	30.88	13.15	-16.03	66.11%	-39.80%
	5	20	80000	0.2	10	1	2613.7	38.26	18.68	-41.60	105.81%	-51.41%
	5	25	80000	0.3	10	1	4863.8	20.56	33.46	112.44	10.60%	-9.58%
	5	25	80000	0.2	10	1	3824.1	26.15	16.51	25.45	40.67%	-28.91%
	5	35	80000	0.3	10	1	5500.6	18.18	72.78	231.37	-2.21%	2.26%
	5	35	80000	0.2	10	1	4928.5	20.29	57.95	185.65	9.14%	-8.38%
c - ν variable	10	30	80000	0.3	10	1	5509.6	18.15	70.78	227.86	-2.37%	2.42%
	10	30	80000	0.2	10	1	4945.6	20.22	56.60	183.34	8.77%	-8.06%
	20	30	80000	0.3	10	1	5621.1	17.79	86.46	277.53	-4.30%	4.50%
	20	30	80000	0.2	10	1	5096.8	19.62	76.62	248.29	5.54%	-5.25%
	50	30	80000	0.3	10	1	5678.6	17.61	96.84	305.21	-5.27%	5.57%
	50	30	80000	0.2	10	1	5168.0	19.35	89.94	284.79	4.09%	-3.93%
	50	15	80000	0.3	10	1	5649.7	17.70	90.91	289.78	-4.79%	5.03%
	50	15	80000	0.2	10	1	5144.0	19.44	84.76	271.55	4.57%	-4.37%
E - ν variable	5	30	40000	0.3	10	1	2699.8	37.04	62.12	198.62	99.25%	-49.81%
	5	30	40000	0.2	10	1	2390.6	41.83	44.87	143.46	125.01%	-55.56%
	5	30	100000	0.3	10	1	6706.9	14.91	55.14	174.90	-19.80%	24.68%
	5	30	100000	0.2	10	1	5963.0	16.77	39.67	126.47	-9.79%	10.85%
	5	30	150000	0.3	10	1	10000.0	10.00	50.35	158.64	-46.21%	85.90%
	5	30	150000	0.2	10	1	8920.6	11.21	36.32	115.50	-39.70%	65.83%
	5	30	200000	0.3	10	1	13315.6	7.51	48.58	152.71	-59.60%	147.54%
	5	30	200000	0.2	10	1	11876.5	8.42	33.60	106.63	-54.71%	120.78%
Ø - ν variable	5	30	80000	0.3	10	0.5	5216.5	19.17	28.26	82.29	Reference model	Reference model
	5	30	80000	0.2	10	0.5	4694.8	21.30	20.33	61.81	11.11%	-10.00%
	5	20	80000	0.3	10	0.5	3219.6	31.06	12.08	-10.65	62.02%	-38.28%
	5	20	80000	0.2	10	0.5	2576.0	38.82	13.75	-20.76	102.50%	-50.62%
	5	25	80000	0.3	10	0.5	4710.3	21.23	19.68	46.84	10.75%	-9.70%
	5	25	80000	0.2	10	0.5	3849.1	25.98	16.11	15.46	35.52%	-26.21%
	5	35	80000	0.3	10	0.5	5271.5	18.97	35.33	97.00	-1.04%	1.05%
	5	35	80000	0.2	10	0.5	4812.3	20.78	29.01	83.39	8.40%	-7.75%
c - ν variable	10	30	80000	0.3	10	0.5	5271.5	18.97	34.56	96.62	-1.04%	1.05%
	10	30	80000	0.2	10	0.5	4805.4	20.81	27.52	81.41	8.56%	-7.88%
	20	30	80000	0.3	10	0.5	5390.8	18.55	42.10	108.51	-3.23%	3.34%
	20	30	80000	0.2	10	0.5	4870.9	20.53	37.12	100.02	7.09%	-6.62%
	50	30	80000	0.3	10	0.5	5316.3	18.81	47.01	113.00	-1.88%	1.91%
	50	30	80000	0.2	10	0.5	4890.0	20.45	42.50	106.48	6.68%	-6.26%
E - ν variable	5	30	40000	0.3	10	0.5	2638.5	37.90	39.19	120.63	97.70%	-49.42%
	5	30	40000	0.2	10	0.5	2364.1	42.30	28.38	89.01	120.66%	-54.68%
	5	30	100000	0.3	10	0.5	6497.7	15.39	25.09	70.67	-19.72%	24.56%
	5	30	100000	0.2	10	0.5	5858.2	17.07	18.06	53.58	-10.95%	12.30%
	5	30	150000	0.3	10	0.5	9689.9	10.32	19.83	51.86	-46.17%	85.76%
	5	30	150000	0.2	10	0.5	8748.9	11.43	16.42	39.71	-40.38%	67.72%
	5	30	200000	0.3	10	0.5	12870.0	7.77	16.95	40.70	-59.47%	146.72%
	5	30	200000	0.2	10	0.5	11641.4	8.59	16.20	31.51	-55.19%	123.17%

- Rows marked with yellow show the Reference models

Table-4. 17 Analysis results for beam: B=5m and H=1m & 0.5m

								PLAXIS Analysis Results				
	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m^3) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'k$_s$' variation from Reference model
Ø - ν variable	5	30	80000	0.3	5	1	7898.9	12.66	31.02	51.38	Reference model	Reference model
	5	**30**	**80000**	**0.2**	**5**	**1**	**7037.3**	**14.21**	**21.38**	**35.39**	**12.24%**	**-10.91%**
	5	20	80000	0.3	5	1	4180.6	23.92	13.93	-14.84	88.94%	-47.07%
	5	**20**	**80000**	**0.2**	**5**	**1**	**3502.6**	**28.55**	**12.83**	**-16.84**	**125.51%**	**-55.66%**
	5	25	80000	0.3	5	1	6447.5	15.51	16.47	18.93	22.51%	-18.38%
	5	**25**	**80000**	**0.2**	**5**	**1**	**5437.7**	**18.39**	**15.27**	**2.62**	**45.26%**	**-31.16%**
	5	35	80000	0.3	5	1	8250.8	12.12	41.61	67.80	-4.27%	4.46%
	5	**35**	**80000**	**0.2**	**5**	**1**	**7524.5**	**13.29**	**33.85**	**55.64**	**4.98%**	**-4.74%**
c - ν variable	10	30	80000	0.3	5	1	8305.6	12.04	42.17	69.38	-4.90%	5.15%
	10	**30**	**80000**	**0.2**	**5**	**1**	**7552.9**	**13.24**	**33.76**	**56.35**	**4.58%**	**-4.38%**
	20	30	80000	0.3	5	1	8569.0	11.67	53.88	89.86	-7.82%	8.48%
	20	**30**	**80000**	**0.2**	**5**	**1**	**7874.0**	**12.70**	**49.26**	**81.81**	**0.32%**	**-0.31%**
	50	30	80000	0.3	5	1	8665.5	11.54	60.50	99.16	-8.85%	9.71%
	50	**30**	**80000**	**0.2**	**5**	**1**	**7974.5**	**12.54**	**56.02**	**92.34**	**-0.95%**	**0.96%**
E - ν variable	5	30	40000	0.3	5	1	3943.2	25.36	31.42	52.08	100.32%	-50.08%
	5	**30**	**40000**	**0.2**	**5**	**1**	**3516.2**	**28.44**	**21.63**	**35.81**	**124.64%**	**-55.49%**
	5	30	100000	0.3	5	1	9881.4	10.12	30.83	51.04	-20.06%	25.10%
	5	**30**	**100000**	**0.2**	**5**	**1**	**8802.8**	**11.36**	**21.30**	**35.26**	**-10.27%**	**11.44%**
	5	30	150000	0.3	5	1	14836.8	6.74	30.39	50.25	-46.76%	87.83%
	5	**30**	**150000**	**0.2**	**5**	**1**	**13227.5**	**7.56**	**21.00**	**34.76**	**-40.28%**	**67.46%**
	5	30	200000	0.3	5	1	19802.0	5.05	29.88	49.36	-60.11%	150.69%
	5	**30**	**200000**	**0.2**	**5**	**1**	**17667.8**	**5.66**	**20.71**	**34.28**	**-55.29%**	**123.67%**
Ø - ν variable	5	30	80000	0.3	5	0.5	7923.9	12.62	26.75	43.85	Reference model	Reference model
	5	**30**	**80000**	**0.2**	**5**	**0.5**	**7082.2**	**14.12**	**18.39**	**30.39**	**11.89%**	**-10.62%**
	5	20	80000	0.3	5	0.5	4175.4	23.95	13.76	-13.57	89.78%	-47.31%
	5	**20**	**80000**	**0.2**	**5**	**0.5**	**3497.7**	**28.59**	**13.15**	**-16.06**	**126.55%**	**-55.86%**
	5	25	80000	0.3	5	0.5	6480.9	15.43	16.56	16.72	22.27%	-18.21%
	5	**25**	**80000**	**0.2**	**5**	**0.5**	**5437.7**	**18.39**	**15.57**	**2.93**	**45.72%**	**-31.38%**
	5	35	80000	0.3	5	0.5	8163.3	12.25	34.04	55.06	-2.93%	3.02%
	5	**35**	**80000**	**0.2**	**5**	**0.5**	**7423.9**	**13.47**	**27.03**	**44.17**	**6.74%**	**-6.31%**
c - ν variable	10	30	80000	0.3	5	0.5	8223.7	12.16	35.62	58.25	-3.65%	3.78%
	10	**30**	**80000**	**0.2**	**5**	**0.5**	**7518.8**	**13.30**	**29.37**	**48.67**	**5.39%**	**-5.11%**
	20	30	80000	0.3	5	0.5	8410.4	11.89	44.81	73.00	-5.78%	6.14%
	20	**30**	**80000**	**0.2**	**5**	**0.5**	**7758.0**	**12.89**	**40.36**	**66.45**	**2.14%**	**-2.09%**
	50	30	80000	0.3	5	0.5	8474.6	11.80	49.66	73.11	-6.50%	6.95%
	50	**30**	**80000**	**0.2**	**5**	**0.5**	**7830.9**	**12.77**	**45.99**	**73.70**	**1.19%**	**-1.17%**
E - ν variable	5	30	40000	0.3	5	0.5	3971.4	25.18	29.16	48.07	99.52%	-49.88%
	5	**30**	**40000**	**0.2**	**5**	**0.5**	**3548.6**	**28.18**	**20.44**	**33.81**	**123.30%**	**-55.22%**
	5	30	100000	0.3	5	0.5	9891.2	10.11	25.64	41.92	-19.89%	24.83%
	5	**30**	**100000**	**0.2**	**5**	**0.5**	**8833.9**	**11.32**	**17.41**	**28.77**	**-10.30%**	**11.48%**
	5	30	150000	0.3	5	0.5	14792.9	6.76	23.31	37.89	-46.43%	86.69%
	5	**30**	**150000**	**0.2**	**5**	**0.5**	**13157.9**	**7.60**	**15.33**	**25.33**	**-39.78%**	**66.05%**
	5	30	200000	0.3	5	0.5	19646.4	5.09	21.36	34.54	-59.67%	147.94%
	5	**30**	**200000**	**0.2**	**5**	**0.5**	**17699.1**	**5.65**	**15.05**	**24.80**	**-55.23%**	**123.36%**

- Rows marked with yellow show the Reference models

Table-4. 18 Analysis results for beam: B=20m and H=1m & 0.5m

	C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m^3) from PLAXIS	PLAXIS Analysis Results			Settlement variation from Reference model	Spring constant 'k$_s$' variation from Reference model
								Settlement (mm)	V (kN/m)	M (kN.m/m)		
Ø - ν variable	5	30	80000	0.3	20	1	3789.3	26.39	58.96	331.96	Reference model	Reference model
	5	30	80000	0.2	20	1	3351.2	29.84	44.05	261.99	13.07%	-11.56%
	5	20	80000	0.3	20	1	2919.7	34.25	17.20	74.54	29.78%	-22.95%
	5	20	80000	0.2	20	1	2216.8	45.11	17.80	-33.85	70.94%	-41.50%
	5	25	80000	0.3	20	1	3703.7	27.00	38.42	230.90	2.31%	-2.26%
	5	25	80000	0.2	20	1	3076.0	32.51	19.28	106.35	23.19%	-18.82%
	5	35	80000	0.3	20	1	3803.7	26.29	67.22	361.90	-0.38%	0.38%
	5	35	80000	0.2	20	1	3385.2	29.54	54.66	309.23	11.94%	-10.66%
c - ν variable	10	30	80000	0.3	20	1	3805.2	26.28	66.86	361.09	-0.42%	0.42%
	10	30	80000	0.2	20	1	3387.5	29.52	53.22	307.85	11.86%	-10.60%
	20	30	80000	0.3	20	1	3816.8	26.20	77.75	392.06	-0.72%	0.73%
	20	30	80000	0.2	20	1	3416.5	29.27	67.51	364.17	10.91%	-9.84%
	50	30	80000	0.3	20	1	3821.2	26.17	86.76	410.64	-0.83%	0.84%
	50	30	80000	0.2	20	1	3427.0	29.18	80.68	394.36	10.57%	-9.56%
E - ν variable	5	30	40000	0.3	20	1	1932.4	51.75	81.57	494.47	96.10%	-49.00%
	5	30	40000	0.2	20	1	1696.4	58.95	61.27	379.56	123.38%	-55.23%
	5	30	100000	0.3	20	1	4710.3	21.23	52.41	238.77	-19.55%	24.31%
	5	30	100000	0.2	20	1	4173.6	23.96	38.76	226.43	-9.21%	10.14%
	5	30	150000	0.3	20	1	7002.8	14.28	41.94	206.50	-45.89%	84.80%
	5	30	150000	0.2	20	1	6222.8	16.07	30.42	168.01	-39.11%	64.22%
	5	30	200000	0.3	20	1	9293.7	10.76	35.70	161.19	-59.23%	145.26%
	5	30	200000	0.2	20	1	8264.5	12.10	25.37	132.70	-54.15%	118.10%
Ø - ν variable	5	30	80000	0.3	20	0.5	3679.2	27.18	18.55	55.83	Reference model	Reference model
	5	30	80000	0.2	20	0.5	3283.0	30.46	13.61	44.98	12.07%	-10.77%
	5	20	80000	0.3	20	0.5	2877.7	34.75	16.46	23.30	27.85%	-21.78%
	5	20	80000	0.2	20	0.5	2199.7	45.46	15.47	20.89	67.26%	-40.21%
	5	25	80000	0.3	20	0.5	3633.7	27.52	16.17	40.73	1.25%	-1.24%
	5	25	80000	0.2	20	0.5	3042.3	32.87	14.71	23.78	20.93%	-17.31%
	5	35	80000	0.3	20	0.5	3683.2	27.15	24.20	61.85	-0.11%	0.11%
	5	35	80000	0.2	20	0.5	3304.7	30.26	18.02	51.86	11.33%	-10.18%
c - ν variable	10	30	80000	0.3	20	0.5	3684.6	27.14	23.74	61.62	-0.15%	0.15%
	10	30	80000	0.2	20	0.5	3308.0	30.23	17.51	51.56	11.22%	-10.09%
	20	30	80000	0.3	20	0.5	3688.7	27.11	31.04	68.96	-0.26%	0.26%
	20	30	80000	0.2	20	0.5	3320.1	30.12	26.85	61.92	10.82%	-9.76%
	50	30	80000	0.3	20	0.5	3690.0	27.10	37.32	73.96	-0.29%	0.30%
	50	30	80000	0.2	20	0.5	3325.6	30.07	32.60	69.01	10.63%	-9.61%
E - ν variable	5	30	40000	0.3	20	0.5	1848.1	54.11	27.42	104.32	99.08%	-49.77%
	5	30	40000	0.2	20	0.5	1647.2	60.71	18.69	87.16	123.36%	-55.23%
	5	30	100000	0.3	20	0.5	4595.6	21.76	16.30	46.05	-19.94%	24.91%
	5	30	100000	0.2	20	0.5	4100.0	24.39	13.47	36.46	-10.26%	11.44%
	5	30	150000	0.3	20	0.5	6887.1	14.52	13.02	32.66	-46.58%	87.19%
	5	30	150000	0.2	20	0.5	6142.5	16.28	13.18	25.03	-40.10%	66.95%
	5	30	200000	0.3	20	0.5	9174.3	10.90	11.97	25.54	-59.90%	149.36%
	5	30	200000	0.2	20	0.5	8190.0	12.21	13.07	19.25	-55.08%	122.60%

- Rows marked with yellow show the Reference models

Poisson's ratio and settlement variation can be seen in Figure-4.15 below. This relation is given for B=10m, H=1m beam. Similar relation has been observed for beams of different dimensions.

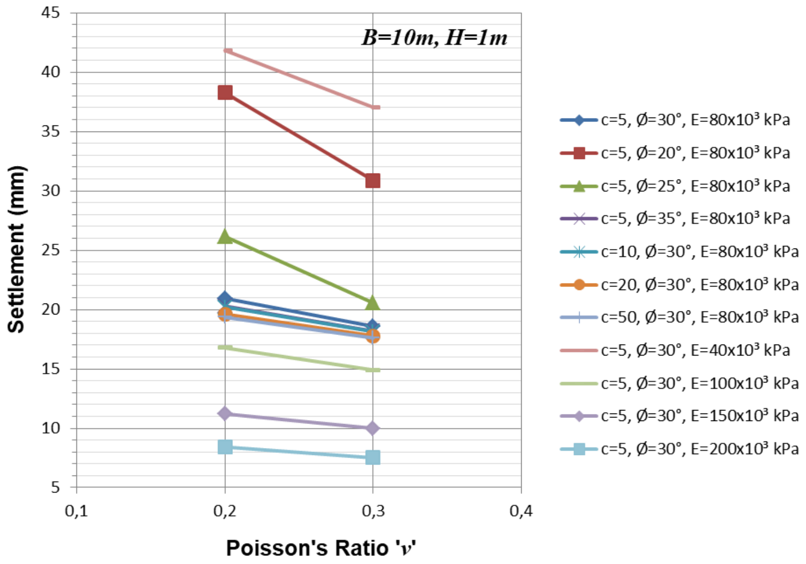


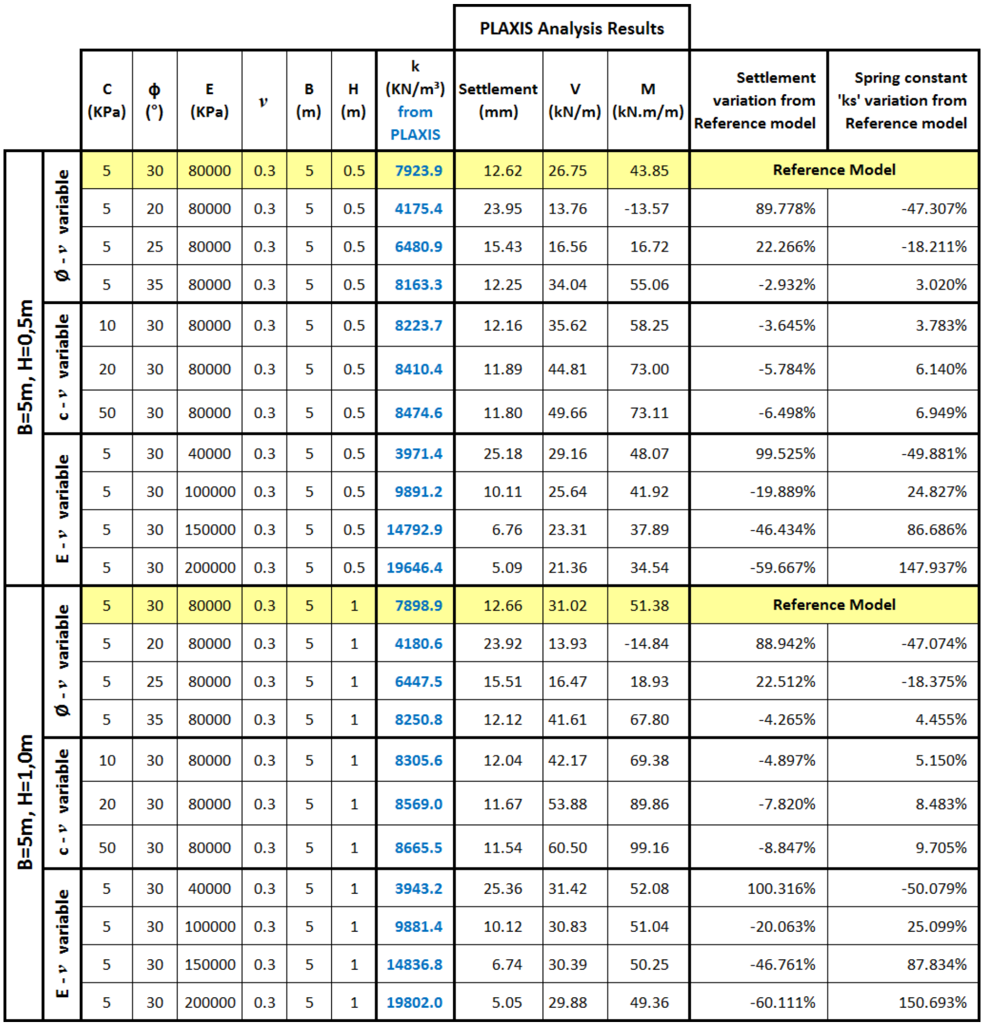
Figure-4. 15 Poisson’s ratio – Settlement variation for B=10m, H=1m beam

As can be seen in tables and figure given above, in soil-foundation models whose Poisson’s ratio equals to 0.2 the settlement values are the higher. From Figure-4.14, it can be concluded that the greater Poisson’s ratio value means the greater lateral strain or smaller linear strain value, likewise, smaller Poisson’s ratio value means the smaller lateral strain or the greater linear strain value. Therefore, in this respect, the results of analyses are consistent. It has been realized that Poisson’s ratio is crucial parameter in terms of stress-deformation characteristics and using in the equation to be proposed can be recommended.

4.2.5 Geometric Properties of Foundation

Width ‘B’ and thickness ‘H’ of foundation member has been dealt with as geometric property. In addition to the aforementioned parameters, geometric properties have been altered and analyses have been repeated. Geometric properties are considerable in terms of defining the flexural rigidity characteristics of foundation. Analysis results that consists the effect of geometric properties have been submitted in Table-4.19 through Table-4.21. Since effect of geometric properties on spring constant is examined in only PLAXIS software in this chapter, only spring constant obtained from PLAXIS has been presented in tables below.

Table-4. 19 Analysis results of B=5m, H=0.5m and B=5m, H=1m (ν=0.3)



									PLAXIS Analysis Results				
		C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'ks' variation from Reference model
B=5m, H=0,5m	Ø - ν variable	5	30	80000	0.3	5	0.5	**7923.9**	12.62	26.75	43.85	**Reference Model**	
		5	20	80000	0.3	5	0.5	**4175.4**	23.95	13.76	-13.57	89.778%	-47.307%
		5	25	80000	0.3	5	0.5	**6480.9**	15.43	16.56	16.72	22.266%	-18.211%
		5	35	80000	0.3	5	0.5	**8163.3**	12.25	34.04	55.06	-2.932%	3.020%
	c - ν variable	10	30	80000	0.3	5	0.5	**8223.7**	12.16	35.62	58.25	-3.645%	3.783%
		20	30	80000	0.3	5	0.5	**8410.4**	11.89	44.81	73.00	-5.784%	6.140%
		50	30	80000	0.3	5	0.5	**8474.6**	11.80	49.66	73.11	-6.498%	6.949%
	E - ν variable	5	30	40000	0.3	5	0.5	**3971.4**	25.18	29.16	48.07	99.525%	-49.881%
		5	30	100000	0.3	5	0.5	**9891.2**	10.11	25.64	41.92	-19.889%	24.827%
		5	30	150000	0.3	5	0.5	**14792.9**	6.76	23.31	37.89	-46.434%	86.686%
		5	30	200000	0.3	5	0.5	**19646.4**	5.09	21.36	34.54	-59.667%	147.937%
B=5m, H=1,0m	Ø - ν variable	5	30	80000	0.3	5	1	**7898.9**	12.66	31.02	51.38	**Reference Model**	
		5	20	80000	0.3	5	1	**4180.6**	23.92	13.93	-14.84	88.942%	-47.074%
		5	25	80000	0.3	5	1	**6447.5**	15.51	16.47	18.93	22.512%	-18.375%
		5	35	80000	0.3	5	1	**8250.8**	12.12	41.61	67.80	-4.265%	4.455%
	c - ν variable	10	30	80000	0.3	5	1	**8305.6**	12.04	42.17	69.38	-4.897%	5.150%
		20	30	80000	0.3	5	1	**8569.0**	11.67	53.88	89.86	-7.820%	8.483%
		50	30	80000	0.3	5	1	**8665.5**	11.54	60.50	99.16	-8.847%	9.705%
	E - ν variable	5	30	40000	0.3	5	1	**3943.2**	25.36	31.42	52.08	100.316%	-50.079%
		5	30	100000	0.3	5	1	**9881.4**	10.12	30.83	51.04	-20.063%	25.099%
		5	30	150000	0.3	5	1	**14836.8**	6.74	30.39	50.25	-46.761%	87.834%
		5	30	200000	0.3	5	1	**19802.0**	5.05	29.88	49.36	-60.111%	150.693%

Except for some of internal forces, considerable difference has not been observed in analysis results between H=0.5m and H=1m beams given in table above. It can be concluded that thickness of beam could not lead too much change.

Table-4. 20 Analysis results of B=10m, H=0.5m and B=10m, H=1m (ν=0.3)

									PLAXIS Analysis Results				
		C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'ks' variation from Reference model
B=10m, H=0,5m	**Ø - ν variable**	5	30	80000	0.3	10	0.5	**5216.5**	19.17	28.26	82.29	**Reference Model**	
		5	20	80000	0.3	10	0.5	**3219.6**	31.06	12.08	-10.65	62.024%	-38.281%
		5	25	80000	0.3	10	0.5	**4710.3**	21.23	19.68	46.84	10.746%	-9.703%
		5	35	80000	0.3	10	0.5	**5271.5**	18.97	35.33	97.00	-1.043%	1.054%
	c - ν variable	10	30	80000	0.3	10	0.5	**5271.5**	18.97	34.56	96.62	-1.043%	1.054%
		20	30	80000	0.3	10	0.5	**5390.8**	18.55	42.10	108.51	-3.234%	3.342%
		50	30	80000	0.3	10	0.5	**5316.3**	18.81	47.01	113.00	-1.878%	1.914%
	E - ν variable	5	30	40000	0.3	10	0.5	**2638.5**	37.90	39.19	120.63	97.705%	-49.420%
		5	30	100000	0.3	10	0.5	**6497.7**	15.39	25.09	70.67	-19.718%	24.561%
		5	30	150000	0.3	10	0.5	**9689.9**	10.32	19.83	51.86	-46.166%	85.756%
		5	30	200000	0.3	10	0.5	**12870.0**	7.77	16.95	40.70	-59.468%	146.718%
B=10m, H=1,0m	**Ø - ν variable**	5	30	80000	0.3	10	1	**5379.2**	18.59	57.35	182.42	**Reference Model**	
		5	20	80000	0.3	10	1	**3238.3**	30.88	13.15	-16.03	66.111%	-39.799%
		5	25	80000	0.3	10	1	**4863.8**	20.56	33.46	112.44	10.597%	-9.582%
		5	35	80000	0.3	10	1	**5500.6**	18.18	72.78	231.37	-2.205%	2.255%
	c - ν variable	10	30	80000	0.3	10	1	**5509.6**	18.15	70.78	227.86	-2.367%	2.424%
		20	30	80000	0.3	10	1	**5621.1**	17.79	86.46	277.53	-4.303%	4.497%
		50	30	80000	0.3	10	1	**5678.6**	17.61	96.84	305.21	-5.272%	5.565%
	E - ν variable	5	30	40000	0.3	10	1	**2699.8**	37.04	62.12	198.62	99.247%	-49.811%
		5	30	100000	0.3	10	1	**6706.9**	14.91	55.14	174.90	-19.796%	24.681%
		5	30	150000	0.3	10	1	**10000.0**	10.00	50.35	158.64	-46.208%	85.900%
		5	30	200000	0.3	10	1	**13315.6**	7.51	48.58	152.71	-59.602%	147.537%

It can be observed in the table given above that the settlement values decreases a bit in the model which beam thickness is 1m in comparison with the model which beam thickness is 0.5m. However, comparison in terms of internal forces between the same models, internal forces have increased considerably. The internal forces did not change much in the models with beam width of 5m. This situation can be interpreted as a result of rigidity of beam increased. Compared to the previous model (B=5m models, Table-4.19), with the effect of increasing beam width, the effect of increasing beam thickness became more noticeable.

Table-4. 21 Analysis results of B=20m, H=0.5m and B=20m, H=1m (ν=0.3)

									PLAXIS Analysis Results				
		C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'ks' variation from Reference model
B=20m, H=0,5m	Ø - ν variable	5	30	80000	0.3	20	0.5	3679.2	27.18	18.55	55.83	Reference Model	
		5	20	80000	0.3	20	0.5	2877.7	34.75	16.46	23.30	27.851%	-21.784%
		5	25	80000	0.3	20	0.5	3633.7	27.52	16.17	40.73	1.251%	-1.235%
		5	35	80000	0.3	20	0.5	3683.2	27.15	24.20	61.85	-0.110%	0.110%
	c - ν variable	10	30	80000	0.3	20	0.5	3684.6	27.14	23.74	61.62	-0.147%	0.147%
		20	30	80000	0.3	20	0.5	3688.7	27.11	31.04	68.96	-0.258%	0.258%
		50	30	80000	0.3	20	0.5	3690.0	27.10	37.32	73.96	-0.294%	0.295%
	E - ν variable	5	30	40000	0.3	20	0.5	1848.1	54.11	27.42	104.32	99.080%	-49.769%
		5	30	100000	0.3	20	0.5	4595.6	21.76	16.30	46.05	-19.941%	24.908%
		5	30	150000	0.3	20	0.5	6887.1	14.52	13.02	32.66	-46.578%	87.190%
		5	30	200000	0.3	20	0.5	9174.3	10.90	11.97	25.54	-59.897%	149.358%
B=20m, H=1,0m	Ø - ν variable	5	30	80000	0.3	20	1	3789.3	26.39	58.96	331.96	Reference Model	
		5	20	80000	0.3	20	1	2919.7	34.25	17.20	74.54	29.784%	-22.949%
		5	25	80000	0.3	20	1	3703.7	27.00	38.42	230.90	2.311%	-2.259%
		5	35	80000	0.3	20	1	3803.7	26.29	67.22	361.90	-0.379%	0.380%
	c - ν variable	10	30	80000	0.3	20	1	3805.2	26.28	66.86	361.09	-0.417%	0.419%
		20	30	80000	0.3	20	1	3816.8	26.20	77.75	392.06	-0.720%	0.725%
		50	30	80000	0.3	20	1	3821.2	26.17	86.76	410.64	-0.834%	0.841%
	E - ν variable	5	30	40000	0.3	20	1	1932.4	51.75	81.57	494.47	96.097%	-49.005%
		5	30	100000	0.3	20	1	4710.3	21.23	52.41	238.77	-19.553%	24.305%
		5	30	150000	0.3	20	1	7002.8	14.28	41.94	206.50	-45.889%	84.804%
		5	30	200000	0.3	20	1	9293.7	10.76	35.70	161.19	-59.227%	145.260%

When the results of Table-4.21 compared with the results of Table-4.20; again, the settlement value of beams with a thickness of 1m is lower than that of beams with a thickness of 0.5m. However, the amount of this reduction was greater in 10m wide beams.

As a summary; i) the increase in thickness did not cause a significant change in 5m wide beams, there was only a slight decrease in the settlement value of the 10m wide beams and ii) the internal forces increased significantly. In the 20m wide beams, the settlement value decreased slightly with increasing thickness, but this decrease was less than 10m wide beams and the internal forces increased excessively. A similar change was observed in models with a Poisson’s ratio of 0.2, but the reduction in settlement values with increasing beam width was even less here as expected.

Thickness of the beam ‘H’ and the settlement variation is given in Figure-4.16 below for different soil parameters and 5m wide beam. In different thickness of beams, similar relation has been observed.

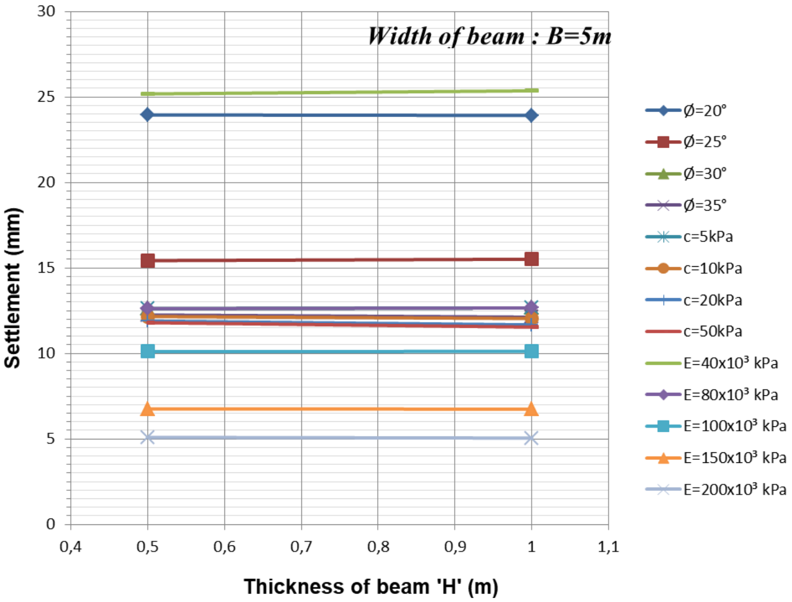


Figure-4. 16 Thickness of beam – Settlement variation for 5m wide beam

The analysis results with Poisson's ratio is 0.2 are presented in Table-4.22 through Table-4.24;

Table-4. 22 Analysis results of B=5m, H=0.5m and B=5m, H=1m (ν=0.2)

									PLAXIS Analysis Results				
		C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'ks' variation from Reference model
B=5m, H=0,5m	Ø - ν variable	5	30	80000	0.2	5	0.5	**7082.2**	14.12	18.39	30.39	**Reference Model**	
		5	20	80000	0.2	5	0.5	**3497.7**	28.59	13.15	-16.06	102.479%	-50.612%
		5	25	80000	0.2	5	0.5	**5437.7**	18.39	15.57	2.93	30.241%	-23.219%
		5	35	80000	0.2	5	0.5	**7423.9**	13.47	27.03	44.17	-4.603%	4.826%
	c - ν variable	10	30	80000	0.2	5	0.5	**7518.8**	13.30	29.37	48.67	-5.807%	6.165%
		20	30	80000	0.2	5	0.5	**7758.0**	12.89	40.36	66.45	-8.711%	9.542%
		50	30	80000	0.2	5	0.5	**7830.9**	12.77	45.99	73.70	-9.561%	10.572%
	E - ν variable	5	30	40000	0.2	5	0.5	**3548.6**	28.18	20.44	33.81	99.575%	-49.894%
		5	30	100000	0.2	5	0.5	**8833.9**	11.32	17.41	28.77	-19.830%	24.735%
		5	30	150000	0.2	5	0.5	**13157.9**	7.60	15.33	25.33	-46.176%	85.789%
		5	30	200000	0.2	5	0.5	**17699.1**	5.65	15.05	24.80	-59.986%	149.912%
B=5m, H=1,0m	Ø - ν variable	5	30	80000	0.2	5	1	**7037.3**	14.21	21.38	35.39	**Reference Model**	
		5	20	80000	0.2	5	1	**3502.6**	28.55	12.83	-16.84	100.915%	-50.228%
		5	25	80000	0.2	5	1	**5437.7**	18.39	15.27	2.62	29.416%	-22.730%
		5	35	80000	0.2	5	1	**7524.5**	13.29	33.85	55.64	-6.474%	6.922%
	c - ν variable	10	30	80000	0.2	5	1	**7552.9**	13.24	33.76	56.35	-6.826%	7.326%
		20	30	80000	0.2	5	1	**7874.0**	12.70	49.26	81.81	-10.626%	11.890%
		50	30	80000	0.2	5	1	**7974.5**	12.54	56.02	92.34	-11.752%	13.317%
	E - ν variable	5	30	40000	0.2	5	1	**3516.2**	28.44	21.63	35.81	100.141%	-50.035%
		5	30	100000	0.2	5	1	**8802.8**	11.36	21.30	35.26	-20.056%	25.088%
		5	30	150000	0.2	5	1	**13227.5**	7.56	21.00	34.76	-46.798%	87.963%
		5	30	200000	0.2	5	1	**17667.8**	5.66	20.71	34.28	-60.169%	151.060%

Table-4. 23 Analysis results of B=10m, H=0.5m and B=10m, H=1m (ν=0.2)

									PLAXIS Analysis Results				
		C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'ks' variation from Reference model
B=10m, H=0,5m	Ø - ν variable	5	30	80000	0.2	10	0.5	**4694.8**	21.30	20.33	61.81	**Reference Model**	
		5	20	80000	0.2	10	0.5	**2576.0**	38.82	13.75	-20.76	82.254%	-45.131%
		5	25	80000	0.2	10	0.5	**3849.1**	25.98	16.11	15.46	21.972%	-18.014%
		5	35	80000	0.2	10	0.5	**4812.3**	20.78	29.01	83.39	-2.441%	2.502%
	c - ν variable	10	30	80000	0.2	10	0.5	**4805.4**	20.81	27.52	81.41	-2.300%	2.355%
		20	30	80000	0.2	10	0.5	**4870.9**	20.53	37.12	100.02	-3.615%	3.751%
		50	30	80000	0.2	10	0.5	**4890.0**	20.45	42.50	106.48	-3.991%	4.156%
	E - ν variable	5	30	40000	0.2	10	0.5	**2364.1**	42.30	28.38	89.01	98.592%	-49.645%
		5	30	100000	0.2	10	0.5	**5858.2**	17.07	18.06	53.58	-19.859%	24.780%
		5	30	150000	0.2	10	0.5	**8748.9**	11.43	16.42	39.71	-46.338%	86.352%
		5	30	200000	0.2	10	0.5	**11641.4**	8.59	16.20	31.51	-59.671%	147.963%
B=10m, H=1,0m	Ø - ν variable	5	30	80000	0.2	10	1	**4775.5**	20.94	41.19	131.44	**Reference Model**	
		5	20	80000	0.2	10	1	**2613.7**	38.26	18.68	-41.60	82.713%	-45.269%
		5	25	80000	0.2	10	1	**3824.1**	26.15	16.51	25.45	24.881%	-19.924%
		5	35	80000	0.2	10	1	**4928.5**	20.29	57.95	185.65	-3.104%	3.204%
	c - ν variable	10	30	80000	0.2	10	1	**4945.6**	20.22	56.60	183.34	-3.438%	3.561%
		20	30	80000	0.2	10	1	**5096.8**	19.62	76.62	248.29	-6.304%	6.728%
		50	30	80000	0.2	10	1	**5168.0**	19.35	89.94	284.79	-7.593%	8.217%
	E - ν variable	5	30	40000	0.2	10	1	**2390.6**	41.83	44.87	143.46	99.761%	-49.940%
		5	30	100000	0.2	10	1	**5963.0**	16.77	39.67	126.47	-19.914%	24.866%
		5	30	150000	0.2	10	1	**8920.6**	11.21	36.32	115.50	-46.466%	86.798%
		5	30	200000	0.2	10	1	**11876.5**	8.42	33.60	106.63	-59.790%	148.694%

Table-4. 24 Analysis results of B=20m, H=0.5m and B=20m, H=1m (ν=0.2)

									PLAXIS Analysis Results				
		C (KPa)	ϕ (°)	E (KPa)	ν	B (m)	H (m)	k (KN/m³) from PLAXIS	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement variation from Reference model	Spring constant 'ks' variation from Reference model
B=20m, H=0,5m	Ø - ν variable	5	30	80000	0.2	20	0.5	3283.0	30.46	13.61	44.98	Reference Model	
		5	20	80000	0.2	20	0.5	2199.7	45.46	15.47	20.89	49.245%	-32.996%
		5	25	80000	0.2	20	0.5	3042.3	32.87	14.71	23.78	7.912%	-7.332%
		5	35	80000	0.2	20	0.5	3304.7	30.26	18.02	51.86	-0.657%	0.661%
	c - ν variable	10	30	80000	0.2	20	0.5	3308.0	30.23	17.51	51.56	-0.755%	0.761%
		20	30	80000	0.2	20	0.5	3320.1	30.12	26.85	61.92	-1.116%	1.129%
		50	30	80000	0.2	20	0.5	3325.6	30.07	32.60	69.01	-1.280%	1.297%
	E - ν variable	5	30	40000	0.2	20	0.5	1647.2	60.71	18.69	87.16	99.311%	-49.827%
		5	30	100000	0.2	20	0.5	4100.0	24.39	13.47	36.46	-19.928%	24.887%
		5	30	150000	0.2	20	0.5	6142.5	16.28	13.18	25.03	-46.553%	87.101%
		5	30	200000	0.2	20	0.5	8190.0	12.21	13.07	19.25	-59.915%	149.468%
B=20m, H=1,0m	Ø - ν variable	5	30	80000	0.2	20	1	3351.2	29.84	44.05	261.99	Reference Model	
		5	20	80000	0.2	20	1	2216.8	45.11	17.80	-33.85	51.173%	-33.851%
		5	25	80000	0.2	20	1	3076.0	32.51	19.28	106.35	8.948%	-8.213%
		5	35	80000	0.2	20	1	3385.2	29.54	54.66	309.23	-1.005%	1.016%
	c - ν variable	10	30	80000	0.2	20	1	3387.5	29.52	53.22	307.85	-1.072%	1.084%
		20	30	80000	0.2	20	1	3416.5	29.27	67.51	364.17	-1.910%	1.947%
		50	30	80000	0.2	20	1	3427.0	29.18	80.68	394.36	-2.212%	2.262%
	E - ν variable	5	30	40000	0.2	20	1	1696.4	58.95	61.27	379.56	97.554%	-49.381%
		5	30	100000	0.2	20	1	4173.6	23.96	38.76	226.43	-19.705%	24.541%
		5	30	150000	0.2	20	1	6222.8	16.07	30.42	168.01	-46.146%	85.688%
		5	30	200000	0.2	20	1	8264.5	12.10	25.37	132.70	-59.450%	146.612%

The increase in thickness had a partial effect on beams of the same width, but this effect could not be interpreted completely as there was no linear change in the comparison of beams of different widths. When the beams of the same thicknesses are compared, the increase in width significantly leads to an increase in settlement values and internal forces.

From these results, it can be concluded that the effect of beam thickness on settlement value is limited and the effect of beam width is higher. Internal forces are more affected by the dimensional changes of the beam compared to the settlement values. Consequently, both beam width and beam thickness are considered to be included in the equation to be proposed.

4.3 Final Results of Analyses

As a summary all results obtained are presented in tabular form. How the formula is obtained will be described in the following sections. All tables can be examined in Table-4.25 through Table-4.30:

Table-4. 25 Ultimate analysis results for B=10m, H=1m

	► ▼	Soil & Foundation Properties ▼						Subgrade Reaction Modulus (kN/m³)		PLAXIS Analysis Results ▼			SAP2000 Analysis Results ▼			Deviations between PLAXIS / SAP as Percentage (%) ▼			
	Model No	C (KPa)	Φ (°)	$E \times 10^3$ (KPa)	ν	B (m)	H (m)	k_s from PLAXIS	k_s from SAP	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	'k_s' Deviation	Settlement Deviation	V Deviation	M Deviation
Ø - ν variable	1	5	30	80	0.3	10	1	5379.2	6000.0	18.59	57.35	182.42	17.06	60.20	167.20	-10.35%	8.96%	-4.73%	9.10%
	2	5	30	80	0.2	10	1	4775.5	5318.2	20.94	41.19	131.44	19.22	60.50	168.28	-10.20%	8.96%	-31.92%	-21.89%
	3	5	20	80	0.3	10	1	3238.3	3590.9	30.88	13.15	-16.03	28.34	61.29	171.08	-9.82%	8.95%	-78.55%	-109.37%
	4	5	20	80	0.2	10	1	2613.7	2893.4	38.26	18.68	-41.60	35.11	61.62	172.24	-9.67%	8.96%	-69.69%	-124.15%
	5	5	25	80	0.3	10	1	4863.8	5418.0	20.56	33.46	112.44	18.87	60.46	168.12	-10.23%	8.97%	-44.65%	-33.12%
	6	5	25	80	0.2	10	1	3824.1	4247.6	26.15	16.51	25.45	24.00	60.99	170.00	-9.97%	8.96%	-72.93%	-85.03%
	7	5	35	80	0.3	10	1	5500.6	6140.0	18.18	72.78	231.37	16.68	60.07	166.70	-10.41%	8.98%	21.15%	38.79%
	8	5	35	80	0.2	10	1	4928.5	5491.0	20.29	57.95	185.65	18.62	60.42	168.01	-10.24%	8.96%	-4.09%	10.50%
c - ν variable	9	10	30	80	0.3	10	1	5509.6	6150.0	18.15	70.78	227.86	16.66	60.08	166.82	-10.41%	8.98%	17.81%	36.59%
	10	10	30	80	0.2	10	1	4945.6	5505.0	20.22	56.60	183.34	18.55	60.87	169.77	-10.16%	8.99%	-7.01%	7.99%
	11	20	30	80	0.3	10	1	5621.1	6275.0	17.79	86.46	277.53	16.33	60.07	166.77	-10.42%	8.97%	43.92%	66.42%
	12	20	30	80	0.2	10	1	5096.8	5681.0	19.62	76.62	248.29	18.01	60.34	167.70	-10.28%	8.96%	26.98%	48.05%
	13	50	30	80	0.3	10	1	5678.6	6340.0	17.61	96.84	305.21	16.16	60.04	166.66	-10.43%	8.97%	61.29%	83.14%
	14	50	30	80	0.2	10	1	5168.0	5761.0	19.35	89.94	284.79	17.76	60.30	167.58	-10.29%	8.96%	49.15%	69.94%
E - ν variable	15	5	30	40	0.3	10	1	2699.8	2990.0	37.04	62.12	198.62	33.99	61.57	172.07	-9.71%	8.98%	0.89%	15.43%
	16	5	30	40	0.2	10	1	2390.6	2645.0	41.83	44.87	143.46	38.39	61.74	172.65	-9.62%	8.97%	-27.32%	-16.91%
	17	5	30	100	0.3	10	1	6706.9	7510.0	14.91	55.14	174.90	13.68	59.53	164.86	-10.69%	9.00%	-7.38%	6.09%
	18	5	30	100	0.2	10	1	5963.0	6662.0	16.77	39.67	126.47	15.39	59.90	166.17	-10.49%	8.97%	-33.78%	-23.89%
	19	5	30	150	0.3	10	1	10000.0	11280.0	10.00	50.35	158.64	9.18	57.96	159.28	-11.35%	8.90%	-13.13%	-0.40%
	20	5	30	150	0.2	10	1	8920.6	10040.0	11.21	36.32	115.50	10.29	58.46	161.08	-11.15%	8.94%	-37.88%	-28.29%
	21	5	30	200	0.3	10	1	13315.6	15140.0	7.51	48.58	152.71	6.90	56.45	153.95	-12.05%	8.90%	-13.94%	-0.80%
	22	5	30	200	0.2	10	1	11876.5	13470.0	8.42	33.60	106.63	7.73	57.09	156.22	-11.83%	9.00%	-41.14%	-31.74%

Table-4. 26 Ultimate analysis results for B=10m, H=0.5m

	► ▼	Soil & Foundation Properties ▼						Subgrade Reaction Modulus (kN/m³)		PLAXIS Analysis Results ▼			SAP2000 Analysis Results ▼			Deviations between PLAXIS / SAP as Percentage (%) ▼			
	Model No	C (KPa)	Φ (°)	$E \times 10^3$ (KPa)	ν	B (m)	H (m)	k_s from PLAXIS	k_s from SAP	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	'k_s' Deviation	Settlement Deviation	V Deviation	M Deviation
Ø - ν variable	23	5	30	80	0.3	10	0.5	5216.5	5582.0	19.17	28.26	82.29	17.59	43.03	111.00	-6.55%	8.98%	-34.32%	-25.86%
	24	5	30	80	0.2	10	0.5	4694.8	4996.0	21.30	20.33	61.81	19.54	44.06	114.67	-6.03%	9.00%	-53.86%	-46.10%
	25	5	20	80	0.3	10	0.5	3219.6	3363.0	31.06	12.08	-10.65	28.50	47.34	126.29	-4.26%	8.98%	-74.48%	-108.43%
	26	5	20	80	0.2	10	0.5	2576.0	2666.0	38.82	13.75	-20.76	35.62	48.95	131.99	-3.38%	8.97%	-71.91%	-115.73%
	27	5	25	80	0.3	10	0.5	4710.3	5013.8	21.23	19.68	46.84	19.48	44.03	114.56	-6.05%	9.01%	-55.30%	-59.11%
	28	5	25	80	0.2	10	0.5	3849.1	4054.0	25.98	16.11	15.46	23.84	45.88	121.10	-5.05%	8.98%	-64.89%	-87.23%
	29	5	35	80	0.3	10	0.5	5271.5	5644.0	18.97	35.33	97.00	17.41	42.92	110.63	-6.60%	8.97%	-17.68%	-12.32%
	30	5	35	80	0.2	10	0.5	4812.3	5126.0	20.78	29.01	83.39	19.07	43.83	113.84	-6.12%	8.96%	-33.81%	-26.75%
c - ν variable	31	10	30	80	0.3	10	0.5	5271.5	5644.0	18.97	34.56	96.62	17.41	42.92	110.63	-6.60%	8.97%	-19.48%	-12.66%
	32	10	30	80	0.2	10	0.5	4805.4	5120.0	20.81	27.52	81.41	19.09	43.84	113.88	-6.14%	9.00%	-37.22%	-28.51%
	33	20	30	80	0.3	10	0.5	5390.8	5778.7	18.55	42.10	108.51	17.02	42.69	109.83	-6.71%	8.96%	-1.39%	-1.20%
	34	20	30	80	0.2	10	0.5	4870.9	5192.0	20.53	37.12	100.02	18.84	43.71	113.42	-6.18%	8.96%	-15.07%	-11.81%
	35	50	30	80	0.3	10	0.5	5316.3	5695.0	18.81	47.01	113.00	17.26	42.80	110.15	-6.65%	8.96%	9.85%	2.58%
	36	50	30	80	0.2	10	0.5	4890.0	5215.2	20.45	42.50	106.48	18.76	43.67	113.27	-6.24%	9.00%	-2.67%	-6.00%
E - ν variable	37	5	30	40	0.3	10	0.5	2638.5	2733.0	37.90	39.19	120.63	34.78	48.79	131.42	-3.46%	8.96%	-19.68%	-8.21%
	38	5	30	40	0.2	10	0.5	2364.1	2438.0	42.30	28.38	89.01	38.83	49.51	133.96	-3.03%	8.93%	-42.68%	-33.56%
	39	5	30	100	0.3	10	0.5	6497.7	7042.0	15.39	25.09	70.67	14.12	40.71	102.81	-7.73%	8.97%	-38.37%	-31.26%
	40	5	30	100	0.2	10	0.5	5858.2	6314.0	17.07	18.06	53.58	15.66	41.82	106.74	-7.22%	9.03%	-56.81%	-49.80%
	41	5	30	150	0.3	10	0.5	9689.9	10766.0	10.32	19.83	51.86	9.47	36.09	86.49	-10.00%	8.98%	-45.06%	-40.04%
	42	5	30	150	0.2	10	0.5	8748.9	9656.0	11.43	16.42	39.71	10.49	37.31	90.79	-9.39%	8.95%	-55.99%	-56.26%
	43	5	30	200	0.3	10	0.5	12870.0	14550.0	7.77	16.95	40.70	7.14	32.69	74.44	-11.55%	8.90%	-48.14%	-45.33%
	44	5	30	200	0.2	10	0.5	11641.4	13075.0	8.59	16.20	31.51	7.89	33.90	78.72	-10.96%	8.89%	-52.21%	-59.97%

Table-4. 27 Ultimate analysis results for B=5m, H=1.0m

	▶ ▼	Soil & Foundation Properties ▼						Subgrade Reaction Modulus (kN/m^3)		PLAXIS Analysis Results ▼			SAP2000 Analysis Results ▼			Deviations between PLAXIS / SAP as Percentage (%) ▼			
	Model No	C (KPa)	Φ (°)	E x 10^3 (KPa)	ν	B (m)	H (m)	k_s from PLAXIS	k_s from SAP	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	'k_s' Deviation	Settlement Deviation	V Deviation	M Deviation
	45	5	30	80	0.3	5	1	7898.9	8692.0	12.66	31.02	51.38	11.62	31.36	44.04	-9.12%	8.95%	-1.09%	16.66%
Ø - ν variable	46	5	30	80	0.2	5	1	7037.3	7744.0	14.21	21.38	35.39	13.04	31.38	44.07	-9.13%	8.98%	-31.87%	-19.70%
	47	5	20	80	0.3	5	1	4180.6	4596.6	23.92	13.93	-14.84	21.96	31.44	44.16	-9.05%	8.95%	-55.69%	-133.60%
	48	5	20	80	0.2	5	1	3502.6	3852.0	28.55	12.83	-16.84	26.20	31.45	44.19	-9.07%	8.99%	-59.20%	-138.11%
	49	5	25	80	0.3	5	1	6447.5	7094.0	15.51	16.47	18.93	14.23	31.39	44.09	-9.11%	8.98%	-47.53%	-57.06%
	50	5	25	80	0.2	5	1	5437.7	5981.4	18.39	15.27	2.62	16.88	31.41	44.12	-9.09%	8.97%	-51.39%	-94.06%
	51	5	35	80	0.3	5	1	8250.8	9080.0	12.12	41.61	67.80	11.12	31.36	44.03	-9.13%	8.96%	32.69%	53.98%
	52	5	35	80	0.2	5	1	7524.5	8280.0	13.29	33.85	55.64	12.20	31.37	44.05	-9.12%	8.97%	7.90%	26.30%
c - ν variable	53	10	30	80	0.3	5	1	8305.6	9140.0	12.04	42.17	69.38	11.05	31.36	44.03	-9.13%	8.96%	34.48%	57.58%
	54	10	30	80	0.2	5	1	7552.9	8310.0	13.24	33.76	56.35	12.15	31.37	44.05	-9.11%	8.95%	7.61%	27.91%
	55	20	30	80	0.3	5	1	8569.0	9430.0	11.67	53.88	89.86	10.71	31.35	44.02	-9.13%	8.95%	71.85%	104.13%
	56	20	30	80	0.2	5	1	7874.0	8665.0	12.70	49.26	81.81	11.66	31.37	44.04	-9.13%	8.97%	57.05%	85.75%
	57	50	30	80	0.3	5	1	8665.5	9536.0	11.54	60.50	99.16	10.59	31.35	44.02	-9.13%	8.95%	92.98%	125.27%
	58	50	30	80	0.2	5	1	7974.5	8775.6	12.54	56.02	92.34	11.51	31.36	44.04	-9.13%	8.96%	78.61%	109.67%
E - ν variable	59	5	30	40	0.3	5	1	3943.2	4336.0	25.36	31.42	52.08	23.27	31.44	44.17	-9.06%	8.97%	-0.06%	17.90%
	60	5	30	40	0.2	5	1	3516.2	3866.4	28.44	21.63	35.81	26.10	31.45	44.19	-9.06%	8.97%	-31.22%	-18.96%
	61	5	30	100	0.3	5	1	9881.4	10880.0	10.12	30.83	51.04	9.29	31.33	43.98	-9.18%	8.98%	-1.59%	16.06%
	62	5	30	100	0.2	5	1	8802.8	9690.0	11.36	21.30	35.26	10.42	31.35	44.01	-9.16%	8.98%	-32.06%	-19.89%
	63	5	30	150	0.3	5	1	14836.8	16350.0	6.74	30.39	50.25	6.19	31.24	43.82	-9.26%	8.97%	-2.71%	14.68%
	64	5	30	150	0.2	5	1	13227.5	14576.0	7.56	21.00	34.76	6.94	31.27	43.87	-9.25%	9.00%	-32.84%	-20.76%
	65	5	30	200	0.3	5	1	19802.0	21840.0	5.05	29.88	49.36	4.64	31.15	43.66	-9.33%	8.95%	-4.07%	13.06%
	66	5	30	200	0.2	5	1	17667.8	19490.0	5.66	20.71	34.28	5.19	31.19	43.73	-9.35%	9.01%	-33.59%	-21.60%

Table-4. 28 Ultimate analysis results for B=5m, H=0.5m

	▶ ▼	Soil & Foundation Properties ▼						Subgrade Reaction Modulus (kN/m^3)		PLAXIS Analysis Results ▼			SAP2000 Analysis Results ▼			Deviations between PLAXIS / SAP as Percentage (%) ▼			
	Model No	C (KPa)	Φ (°)	E x 10^3 (KPa)	ν	B (m)	H (m)	k_s from PLAXIS	k_s from SAP	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	'k_s' Deviation	Settlement Deviation	V Deviation	M Deviation
	67	5	30	80	0.3	5	0.5	7923.9	7914.8	12.62	26.75	43.85	11.58	27.51	38.36	0.12%	8.94%	-2.75%	14.32%
Ø - ν variable	68	5	30	80	0.2	5	0.5	7082.2	7066.0	14.12	18.39	30.39	12.96	27.60	38.52	0.23%	8.93%	-33.36%	-21.10%
	69	5	20	80	0.3	5	0.5	4175.4	4150.8	23.95	13.76	-13.57	21.98	27.91	39.06	0.59%	8.94%	-50.69%	-134.74%
	70	5	20	80	0.2	5	0.5	3497.7	3474.0	28.59	13.15	-16.06	26.24	27.98	39.19	0.68%	8.94%	-53.00%	-140.98%
	71	5	25	80	0.3	5	0.5	6480.9	6461.4	15.43	16.56	16.72	14.16	27.66	38.63	0.30%	8.94%	-40.13%	-56.72%
	72	5	25	80	0.2	5	0.5	5437.7	5414.0	18.39	15.57	2.93	16.88	27.77	38.82	0.44%	8.94%	-43.93%	-92.45%
	73	5	35	80	0.3	5	0.5	8163.3	8154.0	12.25	34.04	55.06	11.25	27.48	38.31	0.11%	8.92%	23.87%	43.71%
	74	5	35	80	0.2	5	0.5	7423.9	7416.0	13.47	27.03	44.17	12.36	27.56	38.45	0.11%	9.02%	-1.92%	14.87%
c - ν variable	75	10	30	80	0.3	5	0.5	8223.7	8214.0	12.16	35.62	58.25	11.17	27.48	38.30	0.12%	8.90%	29.65%	52.07%
	76	10	30	80	0.2	5	0.5	7518.8	7506.0	13.30	29.37	48.67	12.21	27.55	38.43	0.17%	8.94%	6.61%	26.63%
	77	20	30	80	0.3	5	0.5	8410.4	8404.0	11.89	44.81	73.00	10.92	27.46	38.27	0.08%	8.92%	63.21%	90.76%
	78	20	30	80	0.2	5	0.5	7758.0	7754.0	12.89	40.36	66.45	11.82	27.52	38.39	0.05%	9.03%	46.64%	73.10%
	79	50	30	80	0.3	5	0.5	8474.6	8468.0	11.80	49.66	73.11	10.83	27.45	38.26	0.08%	8.92%	80.92%	91.10%
	80	50	30	80	0.2	5	0.5	7830.9	7826.0	12.77	45.99	73.70	11.71	27.52	38.37	0.06%	9.01%	67.15%	92.05%
E - ν variable	81	5	30	40	0.3	5	0.5	3971.4	3946.0	25.18	29.16	48.07	23.12	27.93	39.10	0.64%	8.92%	4.42%	22.93%
	82	5	30	40	0.2	5	0.5	3548.6	3526.0	28.18	20.44	33.81	25.86	27.97	39.18	0.64%	8.98%	-26.93%	-13.71%
	83	5	30	100	0.3	5	0.5	9891.2	9904.0	10.11	25.64	41.92	9.28	27.30	38.00	-0.13%	8.94%	-6.08%	10.33%
	84	5	30	100	0.2	5	0.5	8833.9	8834.0	11.32	17.41	28.77	10.39	27.41	38.19	0.00%	8.95%	-36.49%	-24.67%
	85	5	30	150	0.3	5	0.5	14792.9	14898.0	6.76	23.31	37.89	6.21	26.80	37.12	-0.71%	8.94%	-13.03%	2.09%
	86	5	30	150	0.2	5	0.5	13157.9	13226.0	7.60	15.33	25.33	6.98	26.97	37.41	-0.51%	8.94%	-43.15%	-32.28%
	87	5	30	200	0.3	5	0.5	19646.4	19896.0	5.09	21.36	34.54	4.67	26.33	36.27	-1.25%	8.92%	-18.87%	-4.78%
	88	5	30	200	0.2	5	0.5	17699.1	17886.0	5.65	15.05	24.80	5.19	26.52	36.61	-1.04%	8.95%	-43.24%	-32.25%

Table-4. 29 Ultimate analysis results for B=20m, H=1.0m

		Soil & Foundation Properties ▼						Subgrade Reaction Modulus (kN/m³)		PLAXIS Analysis Results ▼			SAP2000 Analysis Results ▼			Deviations between PLAXIS / SAP as Percentage (%) ▼			
	Model No	C (KPa)	Φ (°)	E x 10^3 (KPa)	ν	B (m)	H (m)	k_s from PLAXIS	k_s from SAP	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	'k_s' Deviation	Settlement Deviation	V Deviation	M Deviation
	89	5	30	80	0.3	20	1	3789.3	4645.0	26.39	58.96	331.96	24.23	76.93	393.11	-18.42%	8.92%	-23.36%	-15.56%
Ø - ν variable	90	5	30	80	0.2	20	1	3351.2	4079.0	29.84	44.05	261.99	27.39	79.94	414.09	-17.84%	8.94%	-44.90%	-36.73%
	91	5	20	80	0.3	20	1	2919.7	3525.0	34.25	17.20	74.54	31.44	83.21	436.90	-17.17%	8.93%	-79.33%	-82.94%
	92	5	20	80	0.2	20	1	2216.8	2637.0	45.11	17.80	-33.85	41.41	89.26	479.19	-15.93%	8.94%	-80.06%	-107.06%
	93	5	25	80	0.3	20	1	3703.7	4534.0	27.00	38.42	230.90	24.79	77.50	397.06	-18.31%	8.93%	-50.43%	-41.85%
	94	5	25	80	0.2	20	1	3076.0	3274.0	32.51	19.28	106.35	29.85	81.99	428.42	-6.05%	8.91%	-76.49%	-75.18%
	95	5	35	80	0.3	20	1	3803.7	4663.0	26.29	67.22	361.90	24.14	76.84	392.48	-18.43%	8.91%	-12.52%	-7.79%
	96	5	35	80	0.2	20	1	3385.2	4122.0	29.54	54.66	309.23	27.12	79.70	412.42	-17.87%	8.92%	-31.42%	-25.02%
c - ν variable	97	10	30	80	0.3	20	1	3805.2	4667.0	26.28	66.86	361.09	24.12	76.82	392.34	-18.47%	8.96%	-12.97%	-7.96%
	98	10	30	80	0.2	20	1	3387.5	4125.0	29.52	53.22	307.85	27.10	79.68	412.30	-17.88%	8.93%	-33.21%	-25.33%
	99	20	30	80	0.3	20	1	3816.8	4680.0	26.20	77.75	392.06	24.06	76.76	391.88	-18.44%	8.91%	1.29%	0.05%
	100	20	30	80	0.2	20	1	3416.5	4162.0	29.27	67.51	364.17	26.87	79.48	410.87	-17.91%	8.92%	-15.06%	-11.37%
	101	50	30	80	0.3	20	1	3821.2	4687.0	26.17	86.76	410.64	24.02	76.72	391.64	-18.47%	8.94%	13.08%	4.85%
	102	50	30	80	0.2	20	1	3427.0	4177.0	29.18	80.68	394.36	26.78	79.40	410.30	-17.96%	8.95%	1.62%	-3.88%
E - ν variable	103	5	30	40	0.3	20	1	1932.4	2283.0	51.75	81.57	494.47	47.50	92.02	498.41	-15.36%	8.94%	-11.35%	-0.79%
	104	5	30	40	0.2	20	1	1696.4	1992.0	58.95	61.27	379.56	54.11	94.45	515.40	-14.84%	8.94%	-35.13%	-26.36%
	105	5	30	100	0.3	20	1	4710.3	5852.0	21.23	52.41	238.77	19.49	71.44	354.76	-19.51%	8.96%	-26.63%	-32.69%
	106	5	30	100	0.2	20	1	4173.6	5147.0	23.96	38.76	226.43	21.99	74.51	376.20	-18.91%	8.95%	-47.98%	-39.81%
	107	5	30	150	0.3	20	1	7002.8	8904.0	14.28	41.94	206.50	13.11	61.35	284.45	-21.35%	8.89%	-31.64%	-27.40%
	108	5	30	150	0.2	20	1	6222.8	7860.0	16.07	30.42	168.01	14.75	64.33	305.16	-20.83%	8.93%	-52.71%	-44.94%
	109	5	30	200	0.3	20	1	9293.7	11977.0	10.76	35.70	161.19	9.90	54.54	237.03	-22.40%	8.65%	-34.54%	-32.00%
	110	5	30	200	0.2	20	1	8264.5	10613.0	12.10	25.37	132.70	11.11	57.26	255.99	-22.13%	8.95%	-55.70%	-48.16%

Table-4. 30 Ultimate analysis results for B=20m, H=0.5m

		Soil & Foundation Properties ▼						Subgrade Reaction Modulus (kN/m³)		PLAXIS Analysis Results ▼			SAP2000 Analysis Results ▼			Deviations between PLAXIS / SAP as Percentage (%) ▼			
	Model No	C (KPa)	Φ (°)	E x 10^3 (KPa)	ν	B (m)	H (m)	k_s from PLAXIS	k_s from SAP	Settlement (mm)	V (kN/m)	M (kN.m/m)	Settlement (mm)	V (kN/m)	M (kN.m/m)	'k_s' Deviation	Settlement Deviation	V Deviation	M Deviation
	111	5	30	80	0.3	20	0.5	3679.2	4467.0	27.18	18.55	55.83	24.95	31.69	92.89	-17.64%	8.92%	-41.46%	-39.90%
Ø - ν variable	112	5	30	80	0.2	20	0.5	3283.0	3972.0	30.46	13.61	44.98	27.97	33.12	102.70	-17.35%	8.92%	-58.91%	-56.20%
	113	5	20	80	0.3	20	0.5	2877.7	3467.0	34.75	16.46	23.30	31.90	34.92	115.03	-17.00%	8.94%	-52.86%	-79.74%
	114	5	20	80	0.2	20	0.5	2199.7	2623.0	45.46	15.47	20.89	41.74	39.07	143.66	-16.14%	8.93%	-60.40%	-85.46%
	115	5	25	80	0.3	20	0.5	3633.7	4410.0	27.52	16.17	40.73	25.27	31.84	93.93	-17.60%	8.92%	-49.22%	-56.64%
	116	5	25	80	0.2	20	0.5	3042.3	3672.0	32.87	14.71	23.78	30.18	34.14	109.69	-17.15%	8.93%	-56.92%	-78.32%
	117	5	35	80	0.3	20	0.5	3683.2	4472.0	27.15	24.20	61.85	24.93	31.68	92.80	-17.64%	8.92%	-23.60%	-33.35%
	118	5	35	80	0.2	20	0.5	3304.7	4000.0	30.26	18.02	51.86	27.78	33.04	102.09	-17.38%	8.94%	-45.45%	-49.20%
c - ν variable	119	10	30	80	0.3	20	0.5	3684.6	4474.0	27.14	23.74	61.62	24.92	31.67	92.76	-17.64%	8.93%	-25.04%	-33.57%
	120	10	30	80	0.2	20	0.5	3308.0	4004.0	30.23	17.51	51.56	27.75	33.02	102.01	-17.38%	8.94%	-46.97%	-49.45%
	121	20	30	80	0.3	20	0.5	3688.7	4479.0	27.11	31.04	68.96	24.89	31.66	92.68	-17.65%	8.93%	-1.95%	-25.59%
	122	20	30	80	0.2	20	0.5	3320.1	4019.0	30.12	26.85	61.92	27.65	32.98	101.68	-17.39%	8.94%	-18.57%	-39.11%
	123	50	30	80	0.3	20	0.5	3690.0	4481.0	27.10	37.32	73.96	24.88	31.65	92.64	-17.65%	8.93%	17.91%	-20.16%
	124	50	30	80	0.2	20	0.5	3325.6	4025.0	30.07	32.60	69.01	27.61	32.96	101.56	-17.38%	8.91%	-1.08%	-32.05%
E - ν variable	125	5	30	40	0.3	20	0.5	1848.1	2187.0	54.11	27.42	104.32	49.68	42.11	164.71	-15.50%	8.92%	-34.88%	-36.66%
	126	5	30	40	0.2	20	0.5	1647.2	1939.0	60.71	18.69	87.16	55.73	44.26	179.64	-15.05%	8.93%	-57.77%	-51.48%
	127	5	30	100	0.3	20	0.5	4595.6	5613.0	21.76	16.30	46.05	19.98	29.20	75.94	-18.13%	8.92%	-44.17%	-39.36%
	128	5	30	100	0.2	20	0.5	4100.0	4993.0	24.39	13.47	36.46	22.39	30.43	84.29	-17.88%	8.92%	-55.73%	-56.74%
	129	5	30	150	0.3	20	0.5	6887.1	8484.0	14.52	13.02	32.66	13.33	25.57	52.14	-18.82%	8.92%	-49.07%	-37.36%
	130	5	30	150	0.2	20	0.5	6142.5	7551.0	16.28	13.18	25.03	14.95	26.49	57.93	-18.65%	8.93%	-50.24%	-56.79%
	131	5	30	200	0.3	20	0.5	9174.3	11353.0	10.90	11.97	25.54	10.01	23.58	40.28	-19.19%	8.92%	-49.23%	-36.59%
	132	5	30	200	0.2	20	0.5	8190.0	10118.0	12.21	13.07	19.25	11.21	24.31	44.56	-19.06%	8.92%	-46.24%	-56.80%

4.4 Simplified Procedure for Determining the Subgrade Reaction Modulus 'k_s'

As explained previously, analyses have been performed in PLAXIS and SAP2000 to obtain the similar settlement values with different input parameters. In PLAXIS, the soil is defined with different parameters such as c, ϕ, E, ν etc., where the spring constant k_s is the only parameter related with soil in SAP2000 analysis. By considering both the units and the relations in between the parameters and the settlement values obtained in the previous sections, i) E, ii) B and iii) ν can be selected to be used in the equation which will be used for determining k_s. After defining these important input parameters, the second step is developing a limit state expression that captures these essential parameters. The limit state expression developed at this initial point is presented below in which $\theta_{1,2,\ldots,n}$ are the unknown model coefficients and constants.

$$k_s = \theta_1 * \frac{E}{B} * (\theta_2 - \nu)$$

Equation-4. 1 Likelihood function for subgrade reaction modulus

As part of maximum likelihood methodology, the θ values are estimated which makes the likelihood function maximum. The Equation-4.1 then takes the form:

$$k_s = 0.854 * \frac{E}{B} * (1 - \nu)$$

Equation-4. 2 Preliminary equation for subgrade reaction modulus

For comparison, the subgrade reaction modulus value obtained from the analyses and the formula are plotted in Figure-4.17. In this figure, the bold line shows $\frac{k_{formula}}{k_{analysis}} = 1$ where the dashed lines are the 1:2 and 2:1 lines.

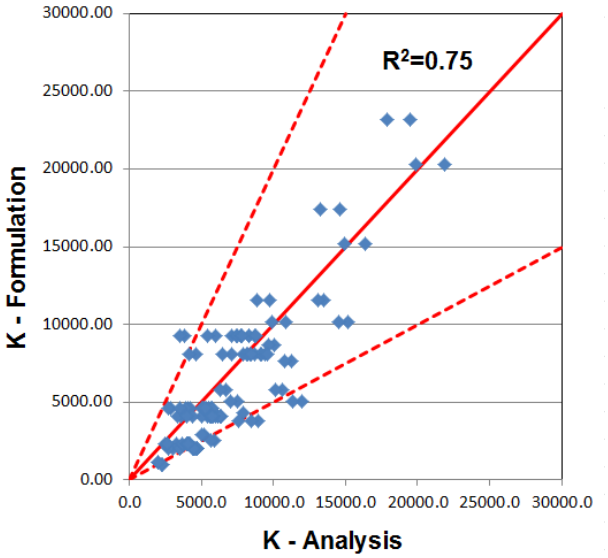


Figure-4. 17 “$k_{formula} – k_{analysis}$” plot of Equation-4.2

It can be seen from Figure-4.17, although some values correspond to each other, most of the values do not correspond to each other ($k_{formula} – k_{analysis}$) which points out a modification in the equation should be proposed. In addition to this, the residual values which are calculated as “ $Residual = ln\left(\frac{k_{formula}}{k_{analysis}}\right)$ ” are also plotted against the variables of the equations. Residual values can be seen in Figure-4.18;

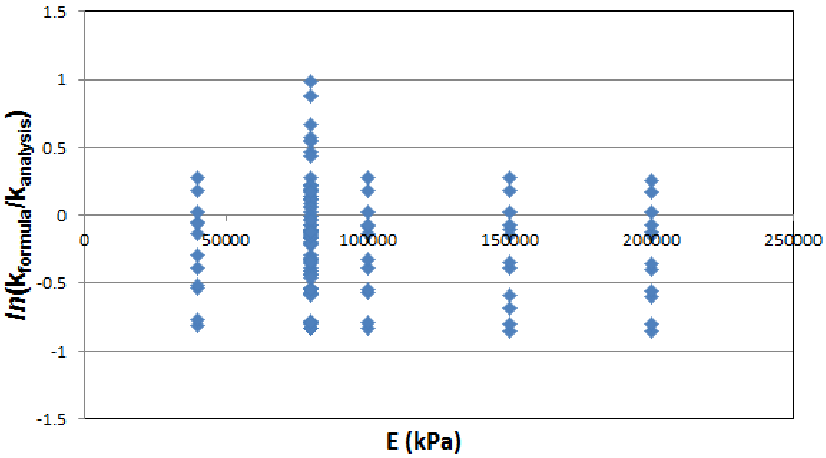


Figure-4. 18 Residual values of Equation-4.2 (for Modulus of Elasticity)

As mentioned previously, more parameters are required for a better estimation of k_s value. The tables 4.26 through 4.31 show that subgrade reaction modulus is directly proportional with Cohesion ‘c’, internal friction angle ‘ϕ’, modulus of elasticity ‘E’, thickness of beam ‘H’ parameters. Width of beam ‘B’ and Poisson’s ratio ‘ν’ parameters are in inversely proportional with subgrade reaction modulus. Accordingly, in a formula to be created as a fraction, directly proportional parameters should be placed in the numerator and inversely proportional parameters in the denominator as can be seen in Equation-4.3. It should be noted that using ‘ϕ’ as directly with own numerical value in the equation may lead to higher deviations, adding as a trigonometric expression will be more accurate probably.

$$k_s \sim \frac{c\ ,\ \phi\ ,\ E\ ,\ H}{B\ ,\ \nu}$$

Equation-4. 3 Approximate draft of subgrade reaction modulus formula

Since it leads to more deviation at the previous attempt of the creating an equation, besides, due to the situation that it will be more accurately that inversely proportional parameters should be placed at denominator as mentioned in previous paragraph, expression of "(1 – ν)" is placed at denominator.

$$k_s = \theta_1 * \frac{E}{B^{\theta 2}\ .\ (\theta_3 - \nu)}$$

Equation-4. 4 Second version of likelihood function for subgrade reaction modulus

In accordance with the previous expressions, E is placed at numerator and B is placed at denominator. Using likelihood methodology, the Equation-4.4 then takes the form:

$$k_s = 0.146 * \frac{E}{B^{0.445}\ .\ (1 - \nu)}$$

Equation-4. 5 Second version of the equation for subgrade reaction modulus

The comparison of the results obtained from this equation and the analysis is presented in Figure-4.19 and residual values is presented in Figure-4.20. Although this equation is a better approximation than the previous one, in order to include all parameters mentioned before and to obtain a more consistent equation, a further step is needed to modify the equation.

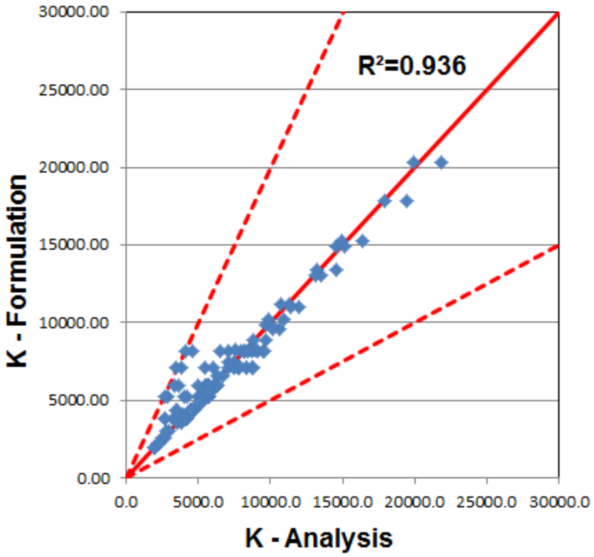


Figure-4. 19 “$k_{formula}$ – $k_{analysis}$” plot of Equation-4.5

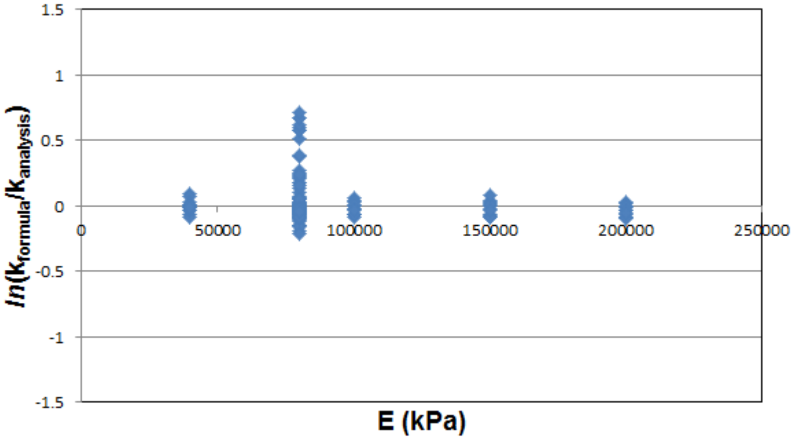


Figure-4. 20 Residual values of Equation-4.5 (for Modulus of Elasticity)

After testing many different alternatives, the best alternative was obtained as presented in Equation-4.6:

$$k_s = 0.0383 \; * \; \frac{E}{B^{0.447} \, . \, (1 - \nu)} \; * \; (1 + \sin\phi)^{2.96} * (1 + H)^{0,284}$$

Equation-4. 6 Final version of the equation for subgrade reaction modulus

Power coefficients of ‘B’, ‘ϕ’ and ‘H’ are rounded up for practical using of the equation. The Equation-4.6 then takes the form;

$$k_s = 0.0383 \; * \; \frac{E}{B^{0.45} \, . \, (1 - \nu)} \; * \; (1 + \sin\phi)^{3} * (1 + H)^{0,3}$$

Equation-4. 7 Proposed equation for determining the subgrade reaction modulus

Similar to the above ones, the comparison of the calculated and the formula results is presented in Figure-4.21. Figure-4.22 through 4.27 show the residual plots. As these figures imply, there Is not a bias against any at the parameters used in the equation.

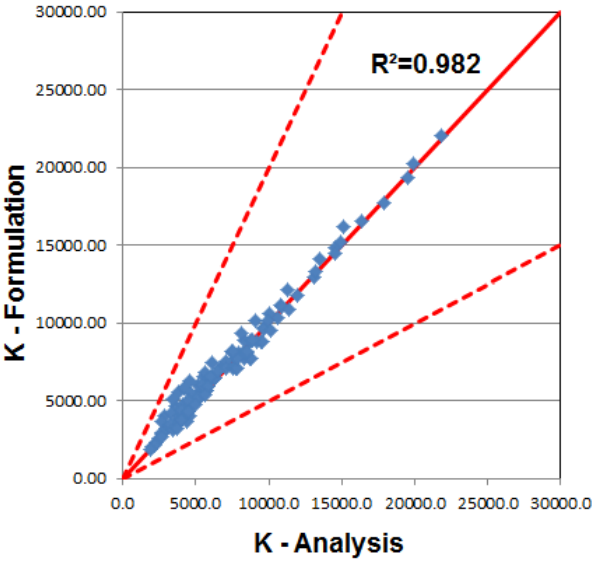


Figure-4. 21 “$k_{formula} – k_{analysis}$” plot of Equation-4.7

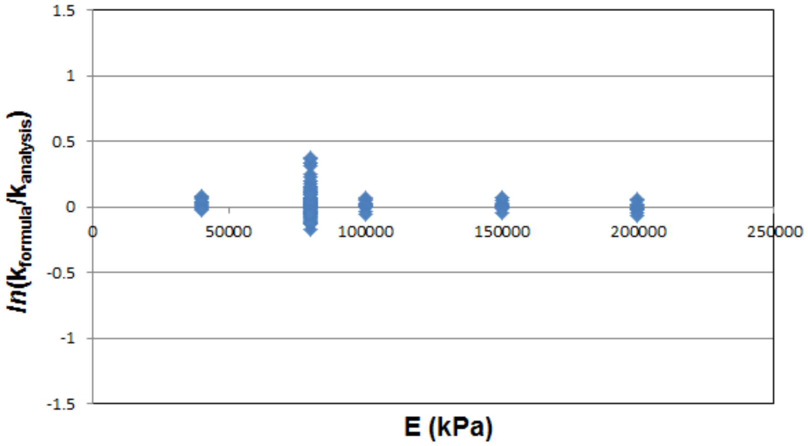


Figure-4. 22 Residual values of Equation-4.7 (for Modulus of Elasticity)

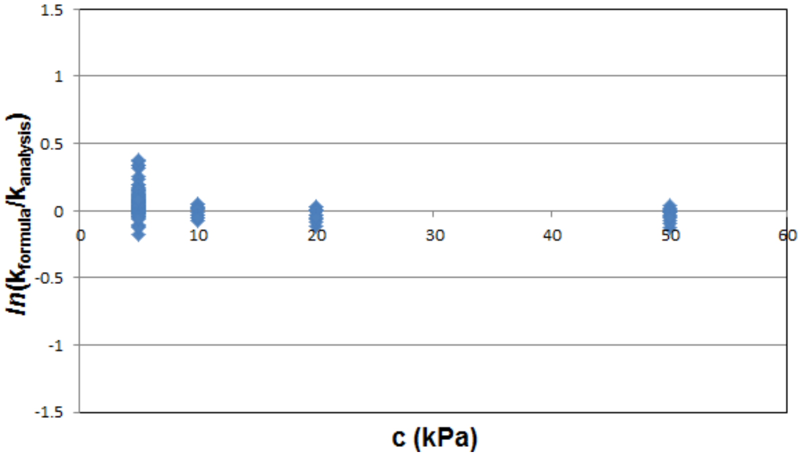


Figure-4. 23 Residual values of Equation-4.7 (for Cohesion)

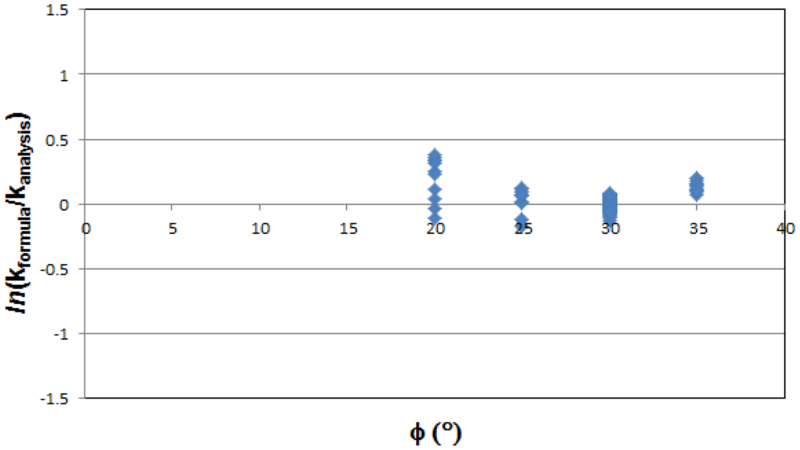


Figure-4. 24 Residual values of Equation-4.7 (for Internal friction angle)

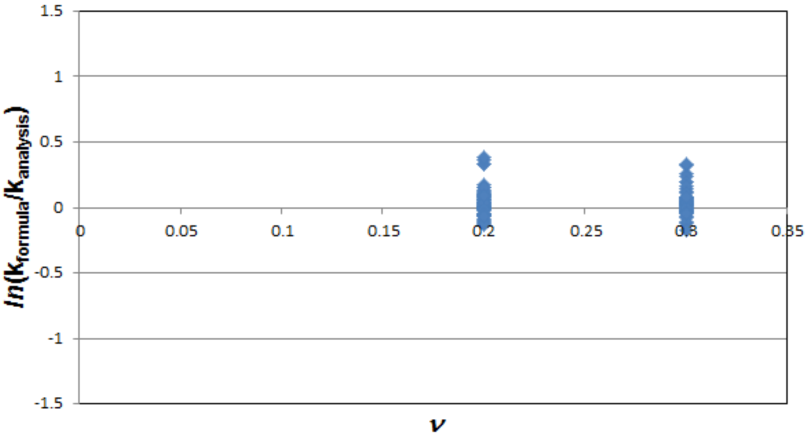


Figure-4. 25 Residual values of Equation-4.7 (for Poisson's ratio)

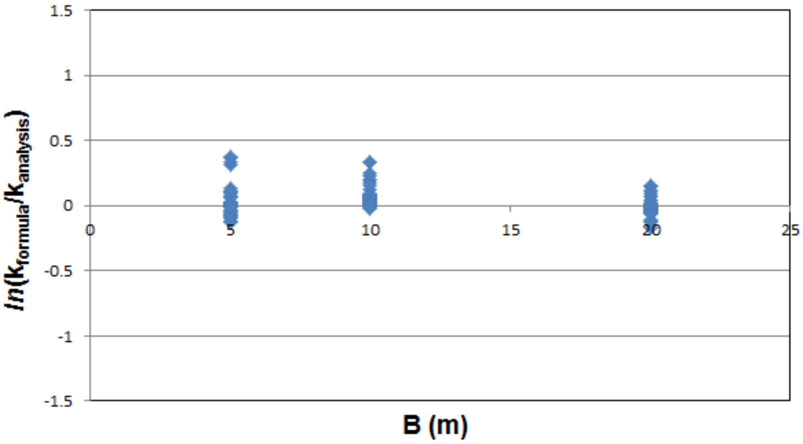


Figure-4. 26 Residual values of Equation-4.7 (for width of the foundation)

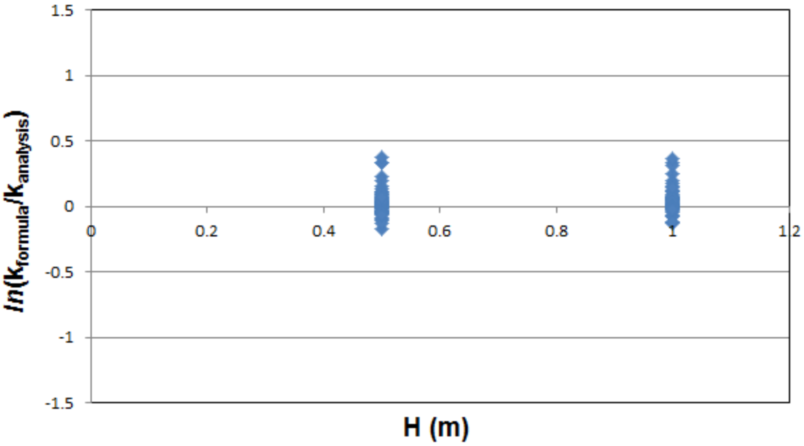


Figure-4. 27 Residual values of Equation-4.7 (for thickness of the foundation)

4.5 Concluding Remarks

In this chapter, the results of the analysis performed by two different numerical analysis softwares are presented. The variation in settlement values with changes in different soil and foundation parameters are presented in detail. Additionally, a simplified procedure for obtaining the soil subgrade modulus is developed within a probabilistic framework using properties of soil (E, ϕ, ν) and foundation (B, H). Resulting formula is presented in Equation-4.7. Final conclusions will be further mentioned in Chapter 5.

5. CONCLUSIONS

Many researchers have studied on subgrade reaction modulus concept. These approaches are based on Winkler foundation model and soil-foundation interaction. When focusing on this concept, while some researchers used basic differential equations that related with this topic, others utilized the empirical conclusions.

In this study, subgrade reaction modulus concept has been examined and numerical modeling has been carried out in accordance with the basic theory of Winkler approach. Generic soil and foundation properties are selected in numerical models performed in PLAXIS and SAP2000 softwares. In the models analyzed using finite element method, different soil parameters and foundation properties have been used. In this parametric study, results are recorded for each case and compared to each other. The main objective was obtaining the similar (at most within 10% deviation range) settlement values in both of these two different platforms.

After being satisfied with the results obtained from these two softwares, the next step is proposing a simplified equation using probabilistic methods. In this equation the main parameters to be included are selected to be the modulus of elasticity (E), internal friction angle (ϕ) and Poisson's ratio (ν) of the soil as well as the width (B) and height (H) of the foundation member. Having tried many alternatives, the most accurate one becomes as follows which is also presented in Equation-4.7 given below;

$$k = 0.0383 \; * \; \frac{E}{B^{0.45} \, . \, (1 - \nu)} \; * (1 + \sin\phi)^3 * (1 + H)^{0,3}$$

It is believed that this equation will contribute to determination of the subgrade reaction modulus using the basic and simple properties of soil and foundation which are calculated in preliminary design steps in each project and will simplify design. This equation is obtained as a result of many different parameters including E, v, ϕ and geometrical parameters of foundation. Therefore, it is considered that the equation can be used for all soil types except for extreme conditions.

However, to obtain a consistent and good result from this study, it should be ensured that the soil parameters are correctly determined. Inconsistent soil parameters can lead to misleading results. In addition, this study has been conducted under uniform loading conditions for elements of wide-use geometry such as foundation beam or raft foundation, and more extensive analyses may be required for extraordinary loading and different geometry conditions.

The following conclusions were reached in this study;

- While modeling foundations on structural analysis softwares, spring zones with different subgrade reaction modules should absolutely be defined at the edges of foundation. As a result of this study, two spring zones are proposed at the edges of foundations (beams in the model). The first zone is the first 13% of the total beam length at the beam ends. The second zone is the 13% of total length after the first zone. Width of foundation can be used instead of length for mat/raft foundations.
- As can be seen in Table-4.1, if the spring zones are defined as 10% of the total length and if the spring constants of the first and second zones are 1.5 and 1.25 times of the normal value respectively, reasonable results can be obtained. However, the results of this study reveals that defining the spring constants of the first and the second zones as 1.56 times and 1.28 times the normal value of subgrade reaction respectively will provides less differences between deviations from the PLAXIS model. Also, springs zones should be 13% of total width (or length) of foundation. Therefore, it is recommended to define the spring zones as shown in Figure-5.1;

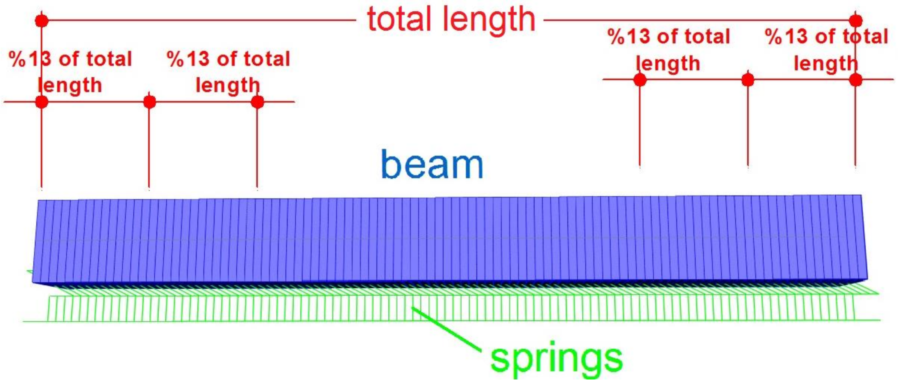


Figure-5. 1 Spring zones recommended

- Since the effect of cohesion ‘c’ on subgrade reaction modulus is very limited, it is not included in the proposed formula.
- Width of foundation ‘B’, thickness of foundation ‘H’ and internal friction angle ‘ϕ’ are the parameters that affect the subgrade reaction modulus to a certain extent. In the equation where these parameters were not used, the values of the subgrade reaction modulus obtained from the formula and analysis showed more deviation from each other, while the consistency was increased with the addition of these parameters. Therefore, it is recommended that these parameters should include in the calculations.
- It should be noted that proposed relation (Equation-4.7) is obtained under boundary conditions below;
  - Modulus of Elasticity ‘E’ : $40000 \text{ kPa} \leq E \leq 200000 \text{ kPa}$
  - Internal friction angle ‘ϕ’ : $20° \leq \phi \leq 35°$
  - Cohesion ‘c’ : $5 \text{ kPa} \leq c \leq 50 \text{ kPa}$
  - Poisson’s ratio ‘v’ : $0.2 \leq v \leq 0.3$
  - Width of foundation ‘B’ : $5\text{m} \leq B \leq 20\text{m}$
  - Thickness of foundation ‘H’ : $0.5\text{m} \leq H \leq 1.0\text{m}$
- It should be kept in mind that the results in this study are only obtained from numerical analysis and no validation with a real case has been performed. For this reason, the design engineers should use it with a great care and if a critical structure is to be designed, a detailed study should be performed instead of using this simplified approach.

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