Limit State Moment Functions for Laterally Loaded Single Piles in Local OC Clay

Aşırı Konsolide Kil Zeminlerdeki Yanal Yüklü Kazıklar için Limit Durum Moment Fonksiyonları

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ABSTRACT

Performance level of piles is usually expressed with the maximum head deflection and bending moment. Uncertainties in the performance of a pile originates from many factors such as spatial variation of soil properties, inadequate soil investigations, errors taking place in the determination of soil parameters by various testing methods, and limited calculation models. These uncertainties make it difficult for practicing engineers to effectively select the appropriate method when designing laterally loaded piles. In this study, the conventional, numerical, two and three dimensional finite element solutions of free head loading conditions are analyzed for determining the maximum deflection and moment of a laterally loaded single concrete pile in a homogenous fully saturated overconsolidated local cohesive soil. The local clay has PI and OCR values of 35 and 6.1, respectively. While developing limit state functions via response surface method, maximum bending moment data under service load condition computed using 3D finite element analysis, which better represents the three dimensional nature of the soil-structure interaction, was used by considering the pile rigidity.

Keywords : *Laterally loaded pile, Oc clay, Pile rigidity, 3-D Finite element analysis, Response surface method, Limit state moment function.*

ÖZET

Kazıkların performans düzeyleri genellikle maksimum kazık başı deplasmanı ve maksimum eğilme momenti ile ifade edilir. Kazık performansındaki belirsizlikler; zemin özelliklerindeki bölgesel değişiklikler, yetersiz zemin etüd çalışmaları, zemin parametrelerinin belirlenmesinde farklı deney yöntemlerinden oluşabilecek hatalar ve sinirli hesap modelleri gibi etkenlerden kaynaklanabilmektedir. Bu belirsizlikler, uygulamacı mühendislerin yanal yüklü kazık dizaynı için kullanacakları uygun yöntemi seçebilmesini zorlaştırmaktadır. Bu çalışmada, suya doygun homojen aşırı konsolide yerel bir kil zemindeki serbest başlı kazıkların yanal yükler altında maksimum kazık başı deplasmanı ve maksimum eğilme momenti değerlerini belirlemek için yapılmış olan konvansiyonel, sayısal ve iki ve üç boyutlu sonlu elemanlar analizleri gerçekleştirilmiştir. Yerel kil zeminin plastisite indisi ve aşırı konsolidasyon oranı değerleri sırası ile 35 ve 6.1 dir. Tepki yüzeyi yöntemi ile limit durum fonksiyonları geliştirilirken, servis yükleri altında kazığın üç boyutlu davranışını daha iyi yansıtan üç boyutlu sonlu elemanlar analizi ile kazık rijitliği dikkate alınarak belirlenen maksimum moment değerleri kullanılmıştır.

Anahtar Kelimeler : *Yanal yüklü kazık, Aşırı konsolide kil, Kazık rijitliği, Üç boyutlu sonlu elemanlar analizi, Tepki yüzeyi yöntemi, Limit durum moment fonksiyonu.*

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1. INTRODUCTION

Lateral loads have at least the same importance as axial compressive loads on piles and therefore they must be carefully taken into consideration during design. Lateral loading of a pile may be due to 'active' loading where external loads are applied at the pile head or due to 'passive' loading where lateral movement of the soil induces bending stresses in the pile (Fleming et al., 1994).

Laterally loaded piles must satisfy geotechnical and structural design criteria. In general, geotechnical design criteria dictate pile dimensions (i.e. diameter and length) and pile type. The maximum moment, occurs typically at a depth of 0.1-0.4 times the length of the pile below the surface, in a free-head pile with a horizontal load at the top depends on the relative pile-soil stiffness factor and loading conditions (Hsiung, 2003).

The maximum deflection, on the other hand, usually takes place at the top of the pile. In current design practice where performance based design has become a crucial task in earthquake prone areas, geotechnical engineers are expected to accurately predict both maximum deflection and moment in the design stage.

Modern analysis methods that allow the lateral load-deflection behavior of piles have become available since late 1960s. Broms method is based primarily on the use of limiting values of soil resistance and solution of the static equilibrium of the pile. Lateral deflections at working loads have been calculated using the concept of subgrade reaction. For instance, the response of a single pile subjected to lateral loads has been successfully modeled by means of finite difference method (FDM) using nonlinear p–y curves. The p–y analysis requires use of numerical solution algorithms (Wang and Reese, 1993; Reese and Wang, 1996). In the recent decades, the finite element method (FEM), which is more versatile than the finite difference method, has been widely used as the most efficient means for evaluating soil-pile interaction (Randolph, 1981).

Among these approaches, FEM computed load-deflection curves often satisfy the results of laterally loaded pile field tests since they consider three dimensional and nonlinear behavior of soil around pile (Tand and Vipulanandan 2008). Although this is the case, 3D modeling of the pile and surrounding soil requires labor intensive work during modeling stage resulting in high analyses costs which are not usually justified for majority of the projects. There is still need in practical design tools that enable engineers to achieve performance based pile analysis.

In this study, behavior of both rigid and flexible single concrete piles were taken into consideration using Broms (1964), Murthy and Subba Rao (1995), p-y curve (Reese, 1985), two and three dimensional finite element methods (Randolph, 1981; Brinkgreve and Broere, 2006). Firstly, the service load level corresponding to allowed lateral pile head deformation is computed using Broms method. Rigid and flexible pile cases were then examined by keeping the pile length constant while varying the pile diameter and the undrained shear strength of fully saturated OC clay. It was decided that three dimensional FEM better represents complex nature of the problem. Simple yet still satisfactory limit state moment functions for laterally loaded piles in homogenous cohesive soils are obtained with response surface method (RSM) using the analysis results of 3D FEM.

2. REVIEW OF PREVIOUS STUDIES

The magnitude of the soil reaction to a laterally deforming pile is a function of the pile deflection, which depends on the pile rigidity and loading conditions. Thus solving the behavior of a pile under lateral loading involves solution of a complex soil-structure-interaction problem.

Lateral loads and moments on a vertical pile are resisted by the flexural stiffness of the pile and mobilization of resistance in the surrounding soil as the pile deflects. Figure 1 shows the mechanism where the ultimate soil resistance is mobilized to resist a combination of lateral force (P) and moment (M) applied at the top of a free-head pile.

The ultimate lateral resistance P_u and the corresponding moment M_u can then be related to the ultimate soil resistance p_{xu}. The soil resistance against the lateral movement of the pile can be considered in two components; the

normal force and the shear forces (Briaud and Smith, 1983) as shown in Figure 2.

Lateral capacity of flexible (long) piles is primarily dependent on the yield moment of the pile whereas the lateral capacity of rigid (short) piles is mostly dependent on the soil resistance.

Many researchers (e.g. Brinch Hansen, 1961; Broms, 1964; Poulos, 1971; Randolph, 1981; Reese, 1985; Murthy and Subba Rao, 1995) have investigated the laterally loaded pile behavior and ultimate lateral resistance to piles in cohesive soils.
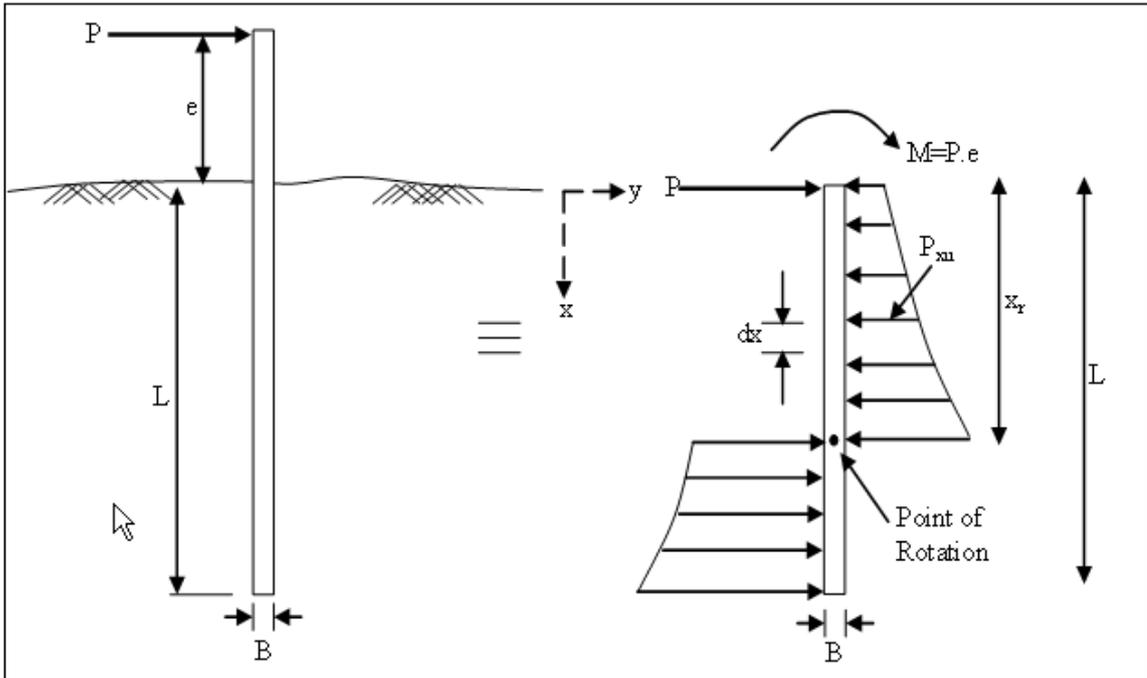
Figure 1. Mobilization of lateral resistance for a free head laterally loaded rigid pile (Prakash and Sharma, 1990).
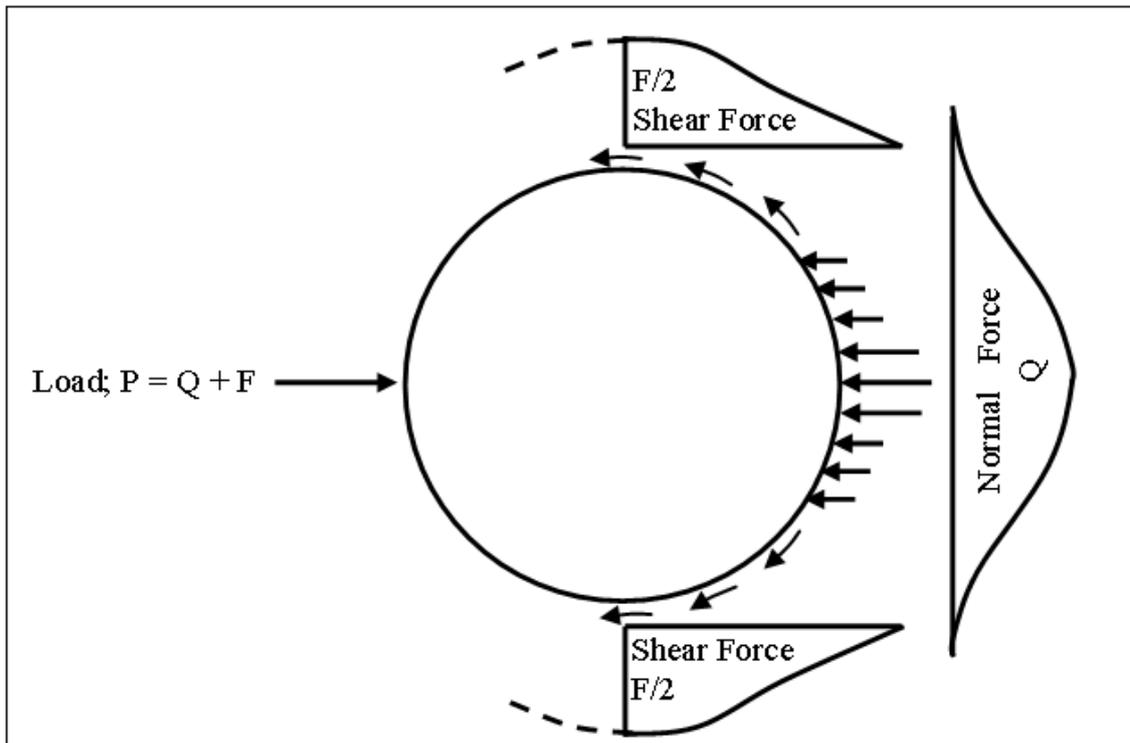
Figure 1. Mobilization of lateral resistance for a free head laterally loaded rigid pile (Prakash and Sharma, 1990).

Methods for calculating lateral resistance of vertical piles can be broadly divided into two categories: (a) Methods for calculating ultimate lateral resistance, and (b) Methods for calculating acceptable deflection at working lateral load. The latter approaches are usually preferred over the ultimate lateral resistance based methods since soil-structure interaction analyses of pile supported structures require evaluation of deformation levels.

One of the well-known methods capable of yielding pile sectional forces and pile deformation is due to Broms (1964). In this approach the soil reaction is related to pile deformation by means of horizontal subgrade modulus (k_h). Although it offers ready-to-use design charts for free and fixed head piles, the Broms method is only applicable to fully homogenous cohesive and cohesionless soils.

In a theoretically more sound approach, Poulos (1971) proposed a linear analysis methodology based on the theory of elasticity where Mindlin's governing equations (1936) are integrated. The soil in this case is assumed as an elastic, homogeneous, isotropic mass having constant elastic parameters E and ν with depth. Also the pile is considered to be a thin vertical strip having with (B), length (L), and constant flexibility ($E_p I_p$). The most significant simplification in Poulos approach is that soil and pile are assumed as fully compatible and horizontal shear stresses developed between the soil and the sides of the pile are not taken into account. The lateral behavior of a pile is influenced by the length-to-diameter ratio, L/B, stiffness of the pile and relative stiffness of the pile/soil material.

Murthy and Subba Rao (1995) developed explicit relationship between coefficient of subgrade modulus, nh, and other soil-pile properties based on dimensional analysis principles. Coefficient of subgrade modulus was expressed as a function of various parameters such as stiffness and diameter of the pile, unit weight and undrained shear strength of the soil.

Other methods that are based on beam on elastic foundation approach are usually considered as derivations of the original Winkler's method (1867). The method is especially suitable to numerical analyses through the discretization of the governing equation (Eq. 1).

$$E_p I_p \frac{d^4 y}{dx^4} + k_h y = 0 \qquad (1)$$

where, E_p is modulus of elasticity of the pile; I_p is the moment of inertia of pile section; x is any point along pile depth; k_h is the modulus of horizontal subgrade reaction; and y is the pile deformation.

Winkler's approach has been later adapted to nonlinear soil-pile interaction analyses by defining nonlinear soil-pile deformation curves (p-y) and interaction models for concrete material (Reese, 1985).

Majority of the available laterally loaded pile analysis methods suffer from the disadvantage of not being able to account for the slippage between the soil and laterally deforming pile. Some p-y models have been proposed in the past for considering gap formation and shear stress generation on soil-pile interface (Nogami et al., 1992). However, their utilization requires establishment of complex p-y curves and numerical solution algorithms.

During the recent decades, FEM has been widely used by researchers. Randolph (1981) performed a parametric study using the 2D FEM for flexible piles in homogeneous soil that was treated as an elastic continuum characterized by a shear modulus (G), Poisson's ratio (υ) and in soil with stiffness proportional to depth rather than by a coefficient of subgrade reaction.

One of the primary advantages of the FEM is that it can be easily extended to a stratified soil medium by taking material nonlinearity and slippage along the soil-pile interface into account within three dimensions. The FEM, however, is computationally expensive compared to other methods since a large number of finite elements with several degrees of freedoms need to be employed in order to accurately model the behavior of the pile.

3. THE SOIL-PILE MODEL

3D FEM using commercially available software, PLAXIS 3D FOUNDATION, was preferred in this study in order to account for soil structure interaction aspects such as soil nonlinearity, soil-pile slippage and relative soil-pile stiffness. The pile-soil model of this study is given in Figure 3.
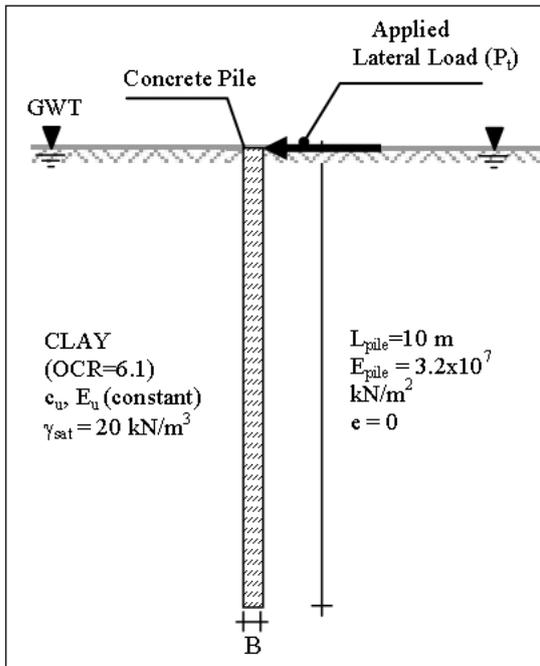
Figure 3. Soil-pile model.

In this model, a free head concrete pile (C30) with an embedment length of 10 m in homogeneous clay is loaded at the top. The soil profile is assumed to be homogeneous with constant deformation modulus (E_u) and undrained shear strength (c_u) values to a depth of 15 m. These two parameters are linked to each other by means of a well known empirical relationship (Eq.2) (Duncan and Buchignani, 1976):

$$E_u = K_{c_u} \times c_u \tag{2}$$

where, E_u is the undrained deformation modulus (kPa), K_{cu} is a factor relating E_u to c_u (Figure 4).
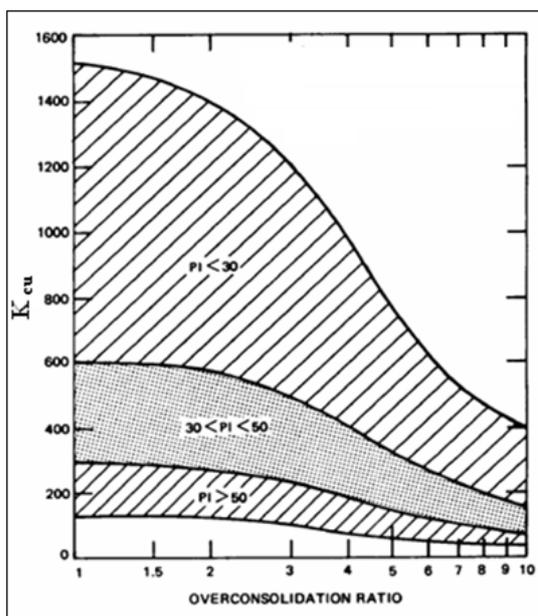
Figure 4. Chart for estimating undrained modulus of clay (compiled from Duncan and Buchignani, 1976).

The plasticity index and overconsolidation parameters are respectively selected as 35 and 6.1 in order to match properties of Gaziemir clay (Kayalar et al., 1991). In this study the empirical adjustment coefficient, K_{cu}, is selected as 200 resulting in the variation of elastic modulus between 1×10^4 and 2×10^4 kN/m².

The length-to-diameter ratio of the pile varied between 8.3 and 25 for a constant pile length of 10 m covering a wide variation range for the pile flexibility parameter, β, as defined by Eq. 3 (Hannigan et al., 1998). The pile is considered as long (i.e. flexible) when βL > 2.25, and short (i.e. rigid) for βL < 2.25.

$$\beta = \left(\frac{k_h B}{4 E_p I_p} \right)^{1/4} \tag{3}$$

In the above equation, $E_p I_p$ is the bending stiffness of the pile section, k_h is the modulus of horizontal subgrade reaction, B and L are the diameter and length of the pile, respectively.

The service load level is defined by factoring the load determined according to Broms Method (Broms, 1964) using the pile diameter, pile length and βL corresponding to the maximum allowable lateral head deflection (y_0).

y_0, the maximum expected value of which is 3.0 cm in this case, is the allowable deflection corresponding to the strain (ε_c) at a stress equal to the maximum stress resulting from the laboratory stress/strain curve. ε_c can be also obtained from the established relationship between c_u and the deformation modulus E_u. The values of ε_c have been established with the range of E_u/c_u of 50 to 200 for most clays and an average value of ε_c is recommended as 0.001 (Matlock, 1970).

$$y_0 = 2.5 \varepsilon_c B \tag{4}$$

Broms Method is one of the well-known and easily applicable for practical design method with offered deflection charts for both rigid and flexible piles. In this approach the soil reaction is related to pile deformation by means of horizontal subgrade modulus (k_h).Typical values of k_h within the critical depth for clays have been accumulated by a formula given below (Broms 1964).

$$k_h = \frac{n_1 n_2 80 q_u}{B} \tag{5}$$

where, q_u=the unconfined compressive strength (kPa); B=the diameter of pile (m); n_1=0.36 (according to unconfined compression strength); n_2=1.15 (for concrete pile). For overconsolidated clay a value of k_h in the range of 2760-16760 kN/m^3 is adopted.

For piles in saturated cohesive soils, using dimensionless length (βL) and maximum allowable lateral pile head deflection (y_0) (i.e. 30 mm), working load Q_a (kN) is obtained with the corresponding value of $y_0 k_h d L / Q_a$ from Figure 5 without eccentricity of loading (e = 0).
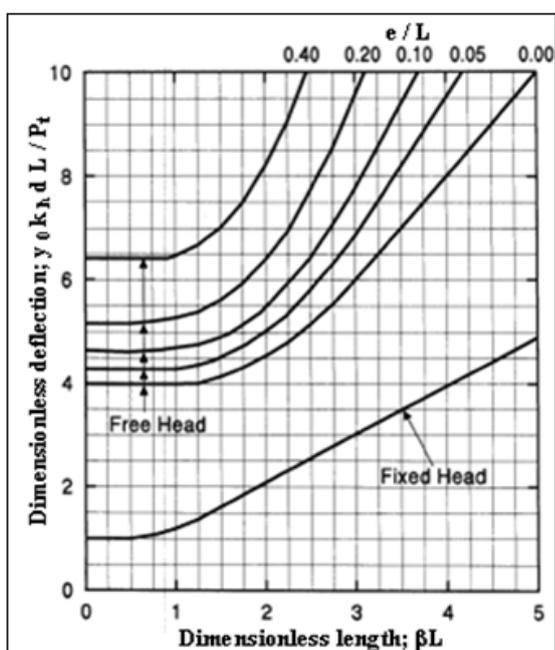
Figure 5. Lateral deflection of pile at ground surface in cohesive soil (Broms 1964).

The factoring coefficient is taken as 2.5 as suggested in the literature (Hannigan et al., 1998). The service loads are given inFigure 6.
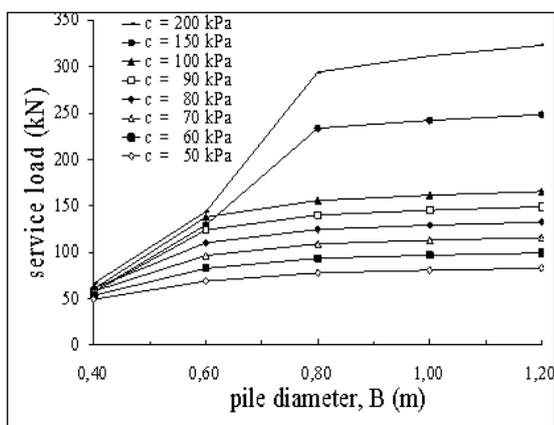
Figure 6. Service loads for FEM analyses.

Such a situation can only be analyzed effectively by means of three-dimensional finite element calculations in which proper models are incorporated to simulate soil behavior and soil-structure interaction. A comprehensive computation of the response of the laterally loaded single pile requires 3D modeling of the problem. The constitutive soil model in FEM analyses was the Mohr-Coulomb model. Soil elements are assumed to be homogeneous and isotropic. Undrained total stress conditions are taken into consideration. The soil-pile interface strength parameter is set to two-thirds of the corresponding soil strength parameter via the interface parameter (R_{inter}) so that strength reduction due to slippage of the soil around the pile is taken into consideration. The pile was modeled as a linear elastic massive circular pile. Details of the soil and pile models are given in Table 1 and Table 2, respectively.

The three dimensional nature of the pile and the surrounding soil was modeled using a fine mesh consisting of 4380 fifteen node wedge elements. The number of finite elements and model dimensions were decided upon numerous FEM analyses trials until discretization and boundary effects became negligible. The square working plane, having dimensions of 40 pile diameters wide by 40 pile diameters long and 2 pile lengths depth, is selected to eliminate the boundary effects and the pile is positioned at the centre of this plane.

Several FEM runs were performed for different pairs of pile diameter and undrained shear strength. Pile diameter varied between 40 and 120 cm whereas the variation range for undrained shear strength was 50 to 200 kPa.

Pile head deformation and bending moment data calculated via the FEM method were found to be in good agreement with those of a previous study (Randolph, 1981). The pile is positioned at the centre of this area. A typical model with the assigned boundary conditions (i.e. constrained in the lateral axis and free to deform along the vertical axis) and the FEM mesh is shown in Figure 7.

Parameter	Name	Value	Unit
Material model	Model	Mohr-Coulomb	-
Type of material behavior	Type	Non - Porous	-
Unit weight of soil above phreatic level	γ_{unsat}	19	kN/m³
Unit weight of soil below phreatic level	γ_{sat}	20	kN/m³
Young's modulus (constant with depth)	E_{ref}	$200 \times c_u$	kN/m²
Poisson's ratio	ν	0.495	-
Undrained cohesion (constant with depth)	c_u	50-60-70-80-90-100-150-200	kN/m²
Friction angle *	ϕ	1	°
Dilatancy angle	ψ	0	°

*: Forr numerical stability purposes.

Table 1. Material properties of the homogeneous cohesive soil.

Parameter	Name	Value	Unit
Material model	Model	Linear Elastic	-
Unit weight of pile	γ	25	kN/m³
Young's modulus (constant)	E_{ref}	3.2×10^7	kN/m²
Poisson's ratio	ν	0.2	-

Table 2. Material properties of the piles.
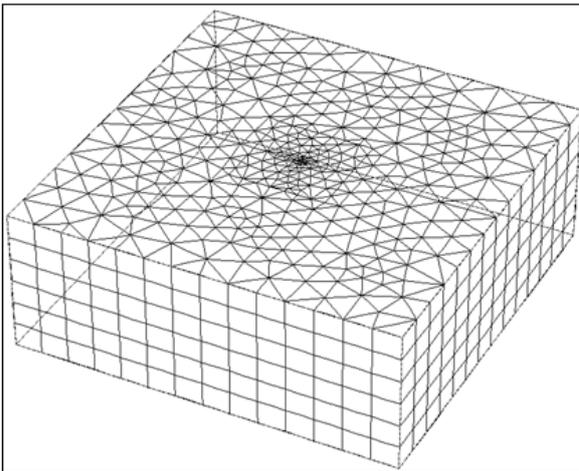
Figure 7. Finite element mesh of the model.

4. ANALYSIS RESULTS AND DISCUSSIONS

An extensive parametric study were carried out by conventional (Broms, Murthy and Subba Rao), numerical (p-y curve method) and two and three dimensional finite element methods (Randolph, Brinkgreve and Broere) to investigate the effects of variation of soil parameters and pile diameters on pile head displacement and maximum moment of a laterally loaded single pile. A free head concrete pile having a 10 meter embedded length in saturated overconsolidated clay was forced on head by a lateral load.

In the analyses, the pile diameter is varied as 40cm, 60cm, 80cm, 100cm and 120cm. whereas the undrained shear strength value ranging from 50 to 200 kPa were used. Analysis results of the pile head displacements and maximum moments are presented and discussed as in the following.

Behavior of laterally loaded pile is a function of the pile soil relative stiffness. Piles are either defined as rigid or flexible piles depending on their deformed shape under lateral load. The pile rigidity factor as defined previously can be used while deciding whether a pile is rigid or flexible. It can be noticed in Figure 8 that the transition from rigid to flexible pile behavior occurs for the data pair of c_u=100kPa and B=60cm.

The variation of maximum moment values with undrained shear strength and pile diameter determined by the mentioned methods is given in Figure 9. As expected, as the pile diameter increases the maximum moment on the pile subjected to different service loads increases as well for both flexible and rigid piles. In the case of flexible pile (B=0.4m and B=0.6m where c_u>100kPa), the maximum moments determined by the mentioned five different methods, are also the same in spite of increasing undrained shear strength. Nevertheless, in the case of rigid piles (B=0.6m where c_u<100 kPa, B=0.8m, 1.0m, 1.2m), the maximum moment values increase parallel to the increasing of undrained shear strength.
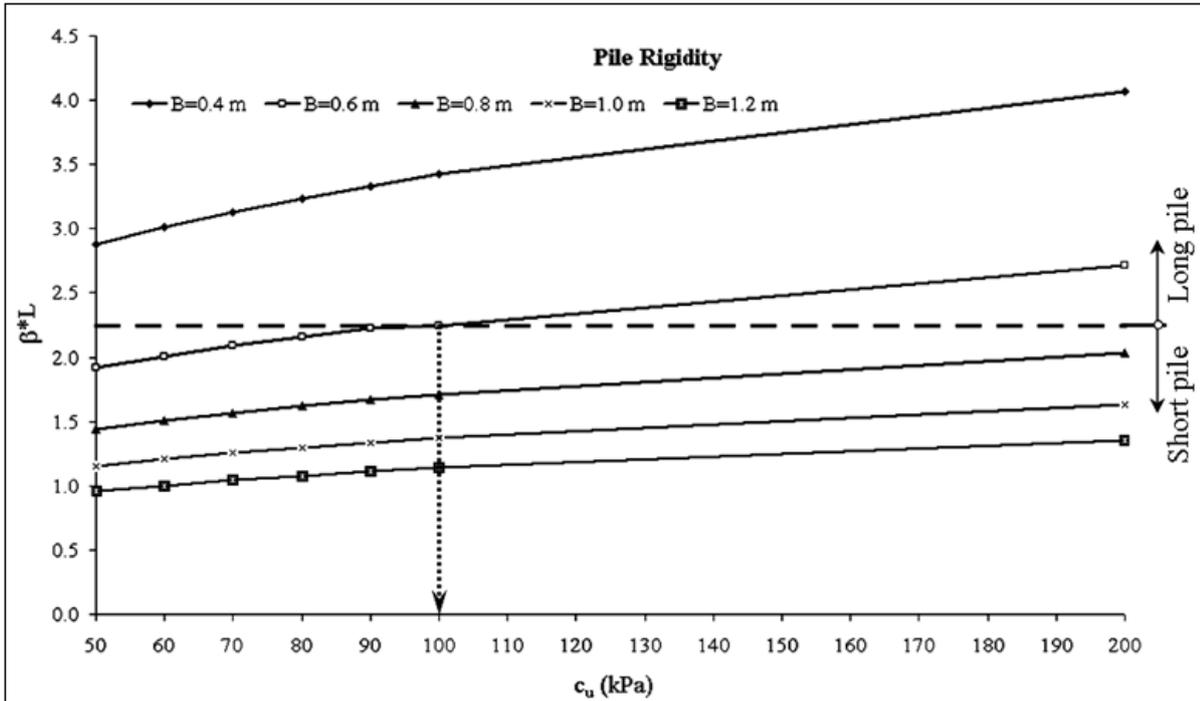
Figure 8. Pile diameter-pile rigidity relationship at various undrained shear strength value.
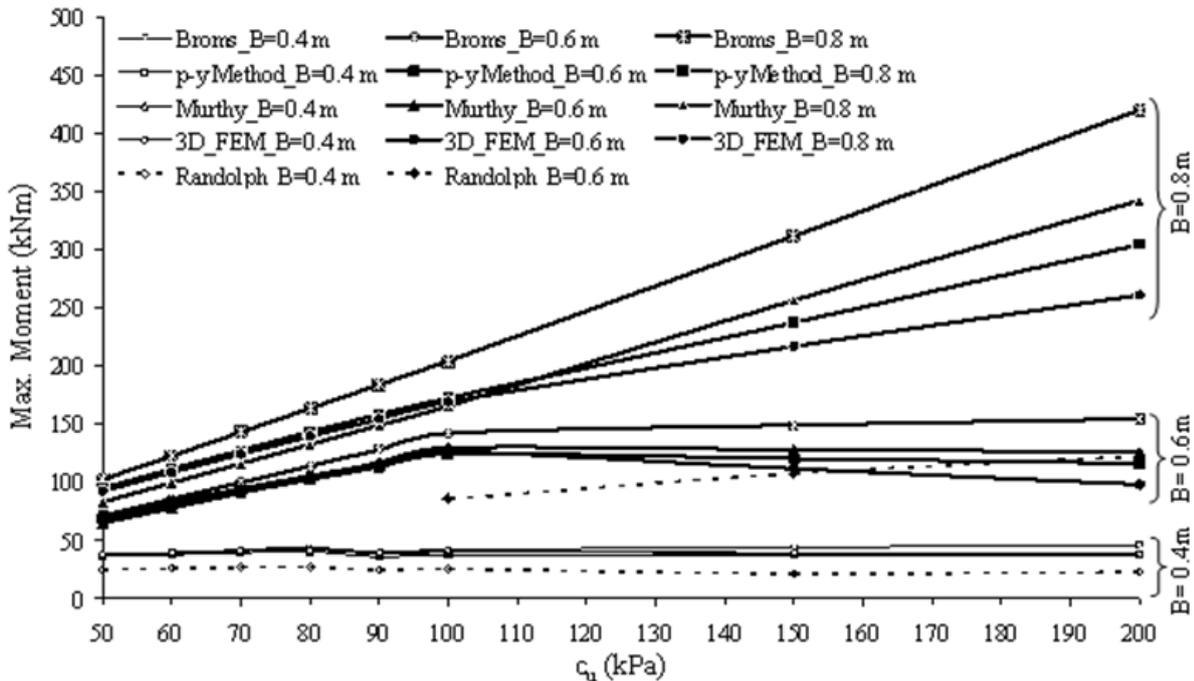
Figure 9. Variation of the maximum bending moment with undrained shear strength and pile diameter.

The Figure 9 clearly indicates that among the piles having the same pile diameter, the moments obtained by Broms method have the greatest value as compared to the other methods.

The results of the analysis for pile head displacement values for regarding to different undrained shear strengths and pile diameters are given in Figure 10.

The head displacement of flexible piles decreases while the shear strength increases, whereas that of rigid piles increases. It can be easily seen in the figure that among the piles that have the same pile diameter and in the same soil condition, the values of pile head displacement obtained by 3-D FEM were really greater than the values obtained by the Murthy, p-y and Randolph methods.
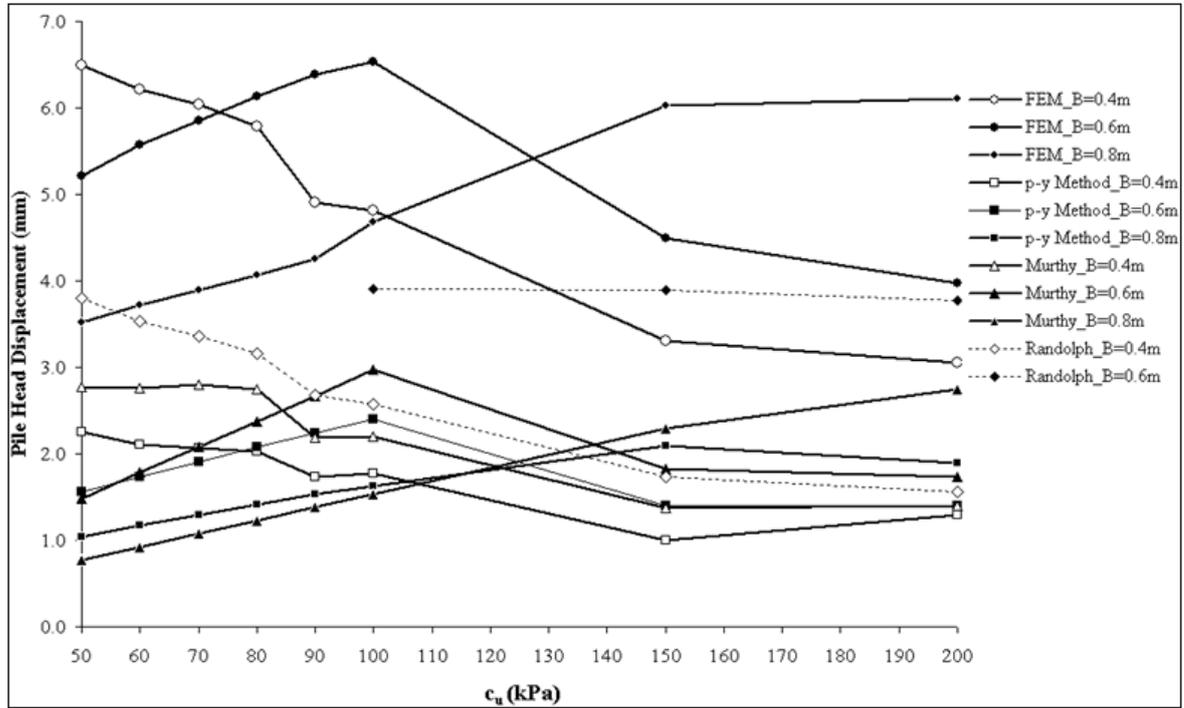
Figure 10. Pile head displacement parameter as a function of undrained shear strength and pile diameter.

5. DEVELOPMENT OF LIMIT STATE MOMENT FUNCTIONS

Contemporary methods for risk assessment and reliability analysis of various geotechnical problems often require development of limit state and performance functions since computational costs can be reduced in this manner by avoiding repeated solutions of governing equations. The multiple linear regressions (MLR) and the response surface methods (RSM) are generally utilized in order to achieve such functions. These approaches have been applied to the reliability analysis of laterally loaded piles, retaining systems and differential settlement problems in the past (Tandjiria et al., 2000; Mahedevan and Shi, 2001; Pula, 2007; Park et al., 2007).

RSM is a collection of statistical and mathematical techniques useful for developing, improving and optimizing process including reduction of variability. In the practical application of RSM, it is necessary to develop an approximating model for the true response surface. Multiple regression is a collection of statistical techniques useful for building the types of empirical models required in RSM. The key ideas in the classical RSM were developed using linear polynomial models, mainly first degree and second degree models, with continuous response variables assumed, for the most part, to be independently and normally distributed with constant error variances. A first order response surface model that might describe the relationship between Y and X_1, X_2,…, Xp is formulated as a linear model

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots\dots + \beta_p X_p + \varepsilon \qquad (6)$$

where β_0, β_1, β_2,….., β_p are constants referred to as the model regression coefficients, *p* is the regressor variable, and ε is a random disturbance or error.

In general, response variable *Y* may be related to *p* regressor variables which model is called a

multiple linear regression model (MLR). MLR attempts to model the relationship between two or more independent variables and a response or dependent variable by fitting a linear equation to observed data. Every value of the independent variable X is associated with a value of the dependent variable Y. (Myers and Montgomery, 2002)

Bending moment is the key parameter for structural design of laterally loaded piles. Deformation criterion for pile performance, however, is implicitly taken into consideration by defining the service lateral load as the forty percent of the load resulting in 30 mm of pile head displacement which is generally accepted.

In this study, maximum bending moment data computed using FEM, which better represented three dimensional nature of the problem upon evaluation of laterally loaded pile analyses results, was used while developing limit state functions via RSM where the pile rigidity is taken into consideration. RSM analyses were examined to find which of the soil and pile properties correlate well with the maximum moment values for both rigid and flexible piles. The undrained shear strength (c_u), which is linearly correlated with elastic modulus of soil (E_u), and the pile diameter (B) were used as independent variables.

The following Limit State Moment Functions have been developed for both rigid (short) and flexible (long) piles (Eq.6 and Eq.7):

Limit State Moment Function for Rigid Piles

$$(LSMFRP) = 151 B\ 1.66\ cu\ 124\ (kNm) \qquad (7)$$

Limit State Moment Function for Flexible Piles

$$(LSMFFP) = 352 B\ 0.0382\ cu\ 97.2\ (kNm) \qquad (8)$$

where the pile diameter (B) is in units of meter, and undrained shear strength (c_u) is in units of kN/m².

The limit state functions as proposed here yield the maximum moment values for both rigid and flexible piles satisfactorily. In these linear relations, the coefficients of correlation (R) for rigid and flexible pile cases were determined as 0.97 and 0.99, respectively. The variation of the

maximum moments estimated using limit state functions are given in Figure 11.

The computed maximum moment via proposed limit state moment functions correlated well with the results of full scale lateral load tests on rigid piles bearing in stiff to very stiff clay at the National Geotechnical Experimentation Site located at the University of Houston in January 1997 (Tand and Vipulanandan 2008). However, additional research needs to be performed to better determine the maximum moment on piles.

Statistics, reliability analysis and risk estimates are important tools to account for uncertainties and to make properly decisions. Hence, probabilistic analysis should be used when uncertainty in parameters may govern the results of the analysis. The probabilistic analyses quantify likelihood of failure from the statistical variations of input parameters or model errors. For instance, the performance functions regarding limit state functions and ultimate design criterion can be utilized in limit state-based reliability analysis which are commonly used the first-order and second-order reliability methods to take into account measurement uncertainties of soil parameters and pile diameter.
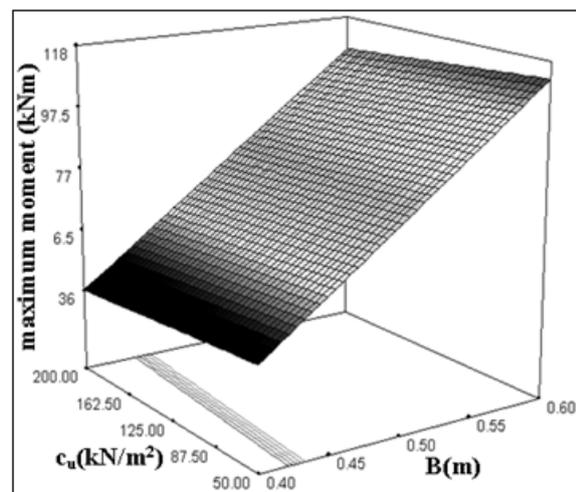
a) Rigid piles.

The analytical models which are most commonly used in practice to predict the maximum moment, as well as acceptable deflection of laterally loaded piles should be calibrated with full-scale load tests to ascertain by pile designers because of the geotechnical uncertainties. Nevertheless, full-scale load tests are generally not performed by designers due to the difficulties and expensiveness except research projects. On the other hand model uncertainties can be significant due to the lack of knowledge and inability to model precisely, and soil-structure interaction behavior. The limit state functions proposed in this study can be used for consideration of uncertainties in undrained shear strength and pile diameter parameters.
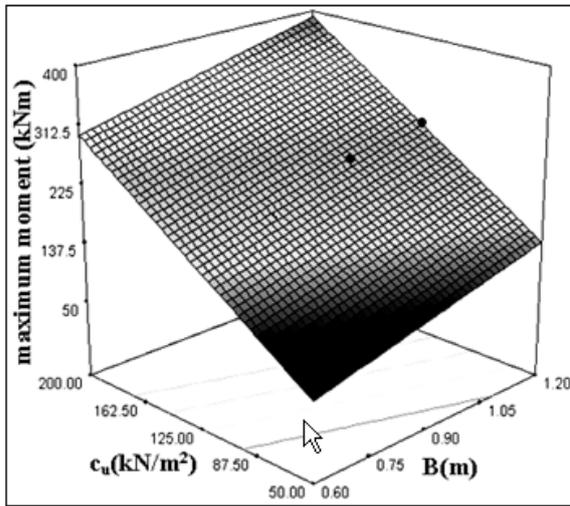
b) Flexible piles

Figure 11. Variation of the estimated maximum pile moment with undrained shear strength and pile diameter.

6. CONCLUSIONS

Numerous analyses were carried out by conventional, numerical and two and three dimensional finite element methods to investigate the effects of pile diameter and undrained shear strength on the response of laterally loaded single pile. This study in this paper leads the following conclusions.

- The maximum bending moment on the flexible pile is approximately constant while increasing undrained shear strength; whereas on the rigid pile it increases parallel to the increasing of undrained shear strength. In another words, bending moment is not as sensitive to undrained shear strength for flexible piles.

- The head displacement of flexible piles decreases whereas that of rigid piles increases; while the undrained shear strength is increasing.

- Analysis results shows that limit state moment functions can be effectively evaluated taking soil-structure-interaction into account. Maximum bending moment is expressed as a linear function of undrained shear strength and pile diameter. The proposed limit state functions should be considered as linear solution planes of the lateral pile response bounded by the prescribed pile head displacement, variation range of the undrained shear strength and pile diameter.

- The relative soil-pile stiffness factor should be determined while utilizing the moment limit state function.

KAYNAKLAR

Briaud, J. L., and Smith, T. D. 1983. "Using the Pressuremeter Curve To Design Laterally Loaded Piles", Proc., 15th Offshore Technology Conf., Houston, USA, Paper. 4501, 495-502.

Brinch Hansen, J. 1961. "The Ultimate Resistance of Rigid Piles against Transversal Forces", Danish Geotechnical Institute Bulletin, Copenhagen, Denmark. (12), 5-9.

Brinkgreve, R.B.J. and Broere W. 2006. Plaxis 3D Foundation Manual. Delft University of Technology & PLAXIS bv, The Netherlands.

Broms, B.B. 1964. Lateral resistance of piles in cohesive soils. Journal of Soil Mechanics and Foundation Division. ASCE. 90 (2), 27-63.

Duncan, J. M., and Buchignani, A. L. 1976. An Engineering Manual for Settlement Studies. Department of Civil Engineering, University of California at Berkeley.

Fleming, W.G. K., Weltman, A. J., Randolph, M. F., Elson, W. K. 1994. Piling Engineering, 2nd Ed., Taylor &Francis.

Hannigan, P.J., Goble, G.G., Thendean, G., Likins, G.E., and Rausche, F. 1998. Design and Construction of Driven Pile Foundation. Workshop Manual Volume I, Technical Report No: FHWA/HI-97-013, US Department of Transportation Federal Highway Administration, Office of Technology Application, Office of Engineering/Bridge Division, Washington, D.C.

Hsuing, Y. 2003. Theoretical elastic-plastic solution for laterally loaded piles. Journal of Geotechnical and Geoenvironmental Engineering, ASCE. (129), 475-480.

Kayalar, A.Ş., Özden, G. ve Ceylan, H. 1991. "Gaziemir (İzmir) Yöresi Zeminlerin Geoteknik Özellikleri", İnşaat Mühendisliğinde Zemin Sempozyumu.

Mahadevan, S and Shi, P. 2001. Multiple linearization method for nonlinear reliability analysis. Journal of Engineering Mechanics, ASCE. 127 (11), 1165-1173.

Matlock, H. 1970. Correliations for Design of Laterally Loaded Piles in Soft Clay. Proceedings of the II Annual Offshore Technology Conference, Houston, Texas (OTC 1204), 577-594.

Mindlin, R.D. 1936. Force at a point in the interior of a semi-infinite solid. Physics. Vol. 7, pp. 195.

Murthy, V.N.S., and Subba Rao, K.S. 1995. Prediction of Nonlinear Behavior of Laterally Loaded Long Piles. Foundation Engineer, New Delhi, Vol. 1 (2).

Myers, R.H. and Montgomery, D.C. 2002. Response Surface Methodology, 2nd ed., John Wiley&Sons, INC.

Nogami, T., Otani J., Konagai, K., and Chen, H. L. 1992. Nonlinear Soil-Pile Interaction Model for Dynamic Lateral Motion. Journal of Geotechnical Engineering, ASCE. 118 (1), 89-106.

Park, J.K., Blackburn, J.T., Gardoni, P. 2007. Reliability Assessment of Excavation Systems Considering Both Stability and Serviceability Performance. Georisk, 1 (3), 123-141.

Poulos, H.G. 1971. Behavior of laterally loaded piles. I: Single Piles. Journal of Soil Mec. and Found. Div., ASCE. 97 (5), 711-731.

Prakash, S. and Sharma, H. D. 1990. Pile Foundations in Engineering Practice. John Willey and Sons, Inc.

Pula, W. 2007. Reliability of Laterally Loaded Rigid Piles. Probabilistic Methods in Geotechnical Engineering, CISM Courses and Lectures, Springer Wien New York, No: 491, 169-183.

Randolph, M. F. 1981. The Response of Flexible Piles to Lateral Loading. Geotechnique, 31 (2), 247-259.

Reese, L.C. 1985. Behavior of Piles and Pile Groups under Lateral Load. Technical Report No: FHWA/RD-85/106, Federal Highway Administration, Office of Engineering and Highway operations, Research and Development, Washington, D.C.

Reese, L.C. and Wang, S.T. 1996. Group 4.0 for Windows, Analysis of a group of piles subjected to axial and lateral loading, Ensoft, Inc., Austin, Tex.

Tand, K.E. and Vipulanandan, C. 2008. "Comparison of Computed vs. Measured Lateral Load/Deflection Response of ACIP Piles", Plaxis Bulletin, Delft, Netherlands. (23), 6-9.

Tandjiria, V., Teh, C.I., Low, B.K. 2000. Reliability analysis of laterally loaded piles using response surface methods. Structural Safety. (22), 335-355.

Wang, S. T., and Reese, L. C. 1993. COM624P-Laterally Loaded Pile Analysis Program for Microcomputer. version 2.0, Final Report FHWA-IP-90-005, Federal Highway Administration, Washington, D.C.

Winkler, E. 1867. Die Lehre von der Elastizität und Festigkeit. Prag. 182.