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**STRESSES AND DISPLACEMENTS
BELOW FOUNDATIONS**

BY
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A THESIS SUBMITTED TO THE
INDIAN INSTITUTE OF TECHNOLOGY, DELHI
FOR THE AWARD OF THE DEGREE OF
DOCTOR OF PHILOSOPHY

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, DELHI

AUGUST, 1980

DEDICATED TO
THE EVERLASTING MEMORY OF
MY LATE REVERED GRANDMOTHER

STRESSES AND DISPLACEMENTS
BELOW FOUNDATIONS

(ii)

CERTIFICATE

This is to certify that the thesis entitled, 'STRESSES AND DISPLACEMENTS BELOW FOUNDATIONS', being submitted by Mr. RAM NARESH SHAHI to the Indian Institute of Technology, Delhi for the award of the Degree of 'DOCTOR OF PHILOSOPHY' is a record of the bonafide research work carried out by him. Mr. Ram Naresh Shahi has worked under my guidance for the submission of this thesis which to my knowledge has reached the requisite standard.

The thesis or any part thereof, has not been submitted to any other University or Institution for the award of any Degree or Diploma.



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ACKNOWLEDGEMENTS

The author expresses his sincere gratitude and profound thankfulness to Dr. Shenbaga R. Kaniraj Jeyachandran, Assistant Professor, Department of Civil Engineering, Indian Institute of Technology, Delhi, for his systematic and valuable guidance and constant encouragement during all the phases of the research work.

The author is specially thankful to Dr. S. Sengupta, Assistant Professor, Department of Applied Mechanics, I. I. T. Delhi, for his invaluable suggestions regarding the analytical investigations of stresses and displacements.

The author is very much obliged to Prof. S.K. Gulhati and Prof. T. Ramamurthy for their keen interest, constant encouragement and unstinted help during the course of this investigation.

The author is very much grateful to the Ministry of Education and Culture, Government of India for providing fellowship under the Quality Improvement Programme and to the Board of Governors, Motilal Nehru Regional Engineering College, Allahabad for sanctioning study leave in order to pursue the research work.

The technical assistance rendered by the staff of Soil Engineering Laboratory, Departmental Workshop and Structural

Engineering Laboratory for the fabrication of test tank and development of instrumentation are gratefully acknowledged. Special mention in this connection is made of Messrs Om Prakash, G.K. Mehta, Badle Ram, P.L. Juneja, T.R. Bhogal, K.K. Bali and R.S. Negi.

The author is specially grateful to Mr. Om Prakash, Senior Laboratory Assistant, Soil Engineering Laboratory, for the uninhibited efforts and constant help during the course of the experimental investigations.

The author is very much thankful to the labourers engaged in the tedious task of sand bed preparation for the experimental investigations.

The author is very much grateful to the staff of computer centre for their help during the course of the analytical investigations.

The author is very much thankful to his colleagues and friends Messrs K.K. Gupta, K.R. Arora, B. Shankariah, T.S. Rekhi, B.S. Satija and C.P. Nag for their help, Co-operation and nice company during the research tenure.

The author is thankful to Mr. N.L. Arora for the preparation of the figures, to Mr. V.P. Gulati for typing the thesis and to Mr. S. Singh for photographic work.

The author is also thankful to his sons Rakesh and Rajesh for their assistance during the experimental investigations.

Finally the author wishes to acknowledge with gratitude the encouragement, patience and forbearance contributed by his wife, Mrs. P. Shahi, during the course of the investigations.

ABSTRACT

Experimental and analytical investigations have been carried out to more closely understand the complex problem of stresses and displacements below foundations. The salient features of the investigations are explained below under three major headings.

I. Experimental Investigations on Settlement Behaviour of Piles and Pile Groups in Sand Including Load Distribution and Load Transfer

There is a lack of reliable quantitative data concerning the behaviour of pile groups in sand. The detailed experimental investigations on pile groups undertaken by Vesic (1967, 69) have also certain limitations because of the procedure of the installation of the pile groups adopted by him. Pointing this out Kaniraj (1974) and Ranganatham and Kaniraj (1978) carried out a comprehensive experimental study on pile groups. The distribution of load among the individual piles of the group, the load transfer and the settlement behaviour of piles and pile groups have not received proper attention by the earlier investigators. Therefore, an experimental investigation on instrumented pile groups has been undertaken to study and comprehend the complex phenomena of load distribution, load transfer and settlement behaviour of pile foundations in sand. The investigations have been carried out

on model aluminium piles of 38 mm outer diameter and 1.80 mm wall thickness with constant L/D (length to diameter) ratio of 15. The variables studied are the spacing of the piles (2D to 5D) and the number of piles (2 to 16) in the group. Diaphragm type pressure cells with bounded electrical resistance strain gauges have been used in order to measure the load distribution among the individual piles of the group and load transfer in the individual piles and pile groups. The experimental investigations have been programmed in such a manner that a comprehensive picture of the behaviour of a pile is obtained at different stages like immediately after its installation, after installation of all the piles in the pile group and after group load tests. The experimental data have been analysed for settlement ratio, group efficiency, load distribution and load transfer. The experimental investigations clearly bring out the pronounced effect of the installation operation of the piles and group loading on the behaviour of the individual piles and pile groups. The details of the experimental investigations are presented in Chapter-2.

II. Analytical Investigations of Stresses and Displacements under Shallow Foundations

Considering the necessity of simple, but rational solutions, the analytical investigations of stresses and

displacements under shallow foundations have been conducted taking into account the non-linear behaviour of the soil and the variable modulus of elasticity. The investigations are based on the work of Hruban (1958). Hruban gave the expressions for the vertical stresses and displacements due to concentrated point loading for different cases of non-linearity and also for different cases of variable modulus of elasticity. These solutions of Hruban have been extended to the development of expressions for vertical stress and displacement below the centre or corner of uniformly loaded circular and rectangular areas and also below the centre of parabolically loaded circular areas. The expressions for the vertical stress and displacement for the various cases of non-linearity and variable modulus of elasticity have been expressed in terms of the intensity of loading (q) and a dimensionless influence factor. The values of the influence factors have been computed for different values of the significant parameters. Chapter-3 presents the details of the analytical investigations.

III. Experimental Investigations of Stresses and Displacements Under Model Footings

In order to measure stress distribution and displacements below shallow foundations and compare these with the predicted values using the theoretical solutions developed in

Chapter-3, experimental investigations have been undertaken on circular, square and rectangular footings resting on dense sand, the details of which are presented in Chapter-4. The vertical stresses below the footings have been measured by embedding diaphragm type pressure cells at different locations. For a few cases the observed values of the stresses and displacements have been compared with the theoretically predicted values making use of solutions developed in Chapter-3.

The results of the entire investigation have been reviewed and evaluated in relation to the practice of deep and shallow foundations in Chapter-5. Following this the conclusions from the various investigations reported in the thesis are summarised in the same Chapter.

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PRINCIPAL NOTATIONS

The following is the general notation adopted in the thesis. Other symbols, as well as the notations below when used to denote something different, are defined in the course of the text.

| | | |
|-------------------|---|---|
| A | - | Radius of circular loaded area |
| a | - | Half the <i>length</i> of rectangular loaded area |
| B | - | Width of the pile group |
| B ₁ | - | Half the thickness of the pressure cell |
| b | - | Half the <i>breadth</i> of rectangular loaded area |
| C _A | - | Pressure cell action factor |
| c | - | Constant, characteristic of the material |
| D | - | Diameter of pile |
| D ₁ | - | Diameter of the pressure cell |
| D' | - | Diameter of diaphragm of pressure cell |
| d | - | A constant |
| E _c | - | Stress/strain modulus of the pressure cell |
| E _s | - | Stress/strain modulus of the soil |
| $\frac{E_c}{E_s}$ | - | Cell to soil stiffness |
| E ₀ | - | Young's modulus of elasticity at surface |
| E _Z | - | Young's modulus of elasticity at depth Z |
| F | - | Flexibility factor $\left(\frac{E_s D'^3}{E_c t'^3} \right)$ |

| | | |
|---------------|---|---|
| F | - | Modulus of deformation $\left(\frac{\sigma_i}{\epsilon_i}\right)$ |
| (Chapter 3) | | |
| f | - | A constant |
| f_d | - | Maximum skin stress in the diaphragm of pressure cell |
| G | - | $\frac{Z}{f}$ |
| g | - | A constant |
| I_{SI} | - | Influence ratio in settlement due to installation of piles |
| I_{SG} | - | Influence ratio due to installation of piles and group load tests |
| I_Z | - | Dimensionless influence factor for vertical stress due to point loading |
| $I_{Z_{LCU}}$ | - | Influence factor for vertical stress under the centre of a uniformly loaded circular area for linear case |
| $I_{Z_{LRU}}$ | - | Influence factor for vertical stress under the corner of a uniformly loaded rectangular area for linear case |
| $I_{Z_{NCP}}$ | - | Influence factor for vertical stress under the centre of a circular area for parabolic loading for non-linear cases |
| $I_{Z_{NCU}}$ | - | Influence factor for vertical stress under the centre of a uniformly loaded circular area for non-linear cases |
| $I_{Z_{NRU}}$ | - | Influence factor for vertical stress under the corner of a uniformly loaded rectangular area for non-linear cases |
| $I_{Z_{VCP}}$ | - | Influence factor for vertical stress under the centre of a circular area for parabolic loading considering variable modulus of elasticity |

- $I_{z_{VCU}}$ - Influence factor for vertical stress under the centre of a uniformly loaded circular area for variable modulus of elasticity
- $I_{z_{VRU}}$ - Influence factor for vertical stress under the corner of a uniformly loaded rectangular area for variable modulus of elasticity
- K' - A constant
- K_1 - Slope of the curve expressing linear increase of Young's modulus with depth.
- K_z - Dimensionless influence factor for vertical displacement due to point loading
- $K_{z_{LCU}}$ - Influence factor for vertical displacement below the centre of a uniformly loaded circular area for linear case
- $K_{z_{LRU}}$ - Influence factor for vertical displacement under the corner of a uniformly loaded rectangular area for linear case
- $K_{z_{NCU}}$ - Influence factor for vertical displacement below the centre of a uniformly loaded circular area for non-linear cases
- $K_{z_{VCP}}$ - Influence factor for vertical displacement below the centre of a circular area with parabolic loading considering variable modulus of elasticity
- $K_{z_{VCU}}$ - Influence factor for vertical displacement below the centre of a uniformly loaded circular area for variable modulus of elasticity
- $K_{z_{VRU}}$ - Influence factor for vertical displacement under the corner of a uniformly loaded rectangular area for variable modulus of elasticity
- L - Length of pile (Chapter 2)
- $-$ Dimensionless parameter $\frac{A}{Z}$ (Chapter 3)
- M - Dimensionless parameter $\frac{a}{b}$

- m - Reciprocal of Poisson's ratio ($\frac{1}{\mu}$)
- m_1 - Dimensionless parameter $\frac{b}{a}$
- N - Dimensionless parameter $\frac{Z}{b}$
- N' - A property of the soil such that N'/D' is analogous to the coefficient of subgrade reaction
- n - Number of piles in a pile group
 (Chapter 2)
- A constant > 1 (Chapter 3)
- n' - Dimensionless parameter $\frac{Z}{A}$
- n_1 - Dimensionless parameter $\frac{Z}{a}$
- P - Concentrated vertical load
- P_g - Ultimate load of the pile group
- P_s - Ultimate load of a single pile
- p - Field stress existing at the *plane* of the pressure cell in its absence
- p_e - Additional pressure recorded by the pressure cell due to its rigidity
- p_{max} - Maximum allowable pressure
- Q - Total load on a pile
- Q_p - Point load on a pile
- q - Average intensity of loading
- q_r - Intensity of loading at distance r from the centre of a circular area for parabolic loading
- q_{max} - Maximum intensity of loading at the centre of a circular area for parabolic loading ($2q$)

(xLv)

- R_{BI} - Reduction factor in bearing capacity due to installation of piles
- R_{BG} - Reduction factor in bearing capacity due to installation of piles and group load tests
- R, φ, ψ - Spherical coordinates
- R - $(r^2 + z^2)^{\frac{1}{2}}$
- R_s - Settlement ratio
- r, θ, z - Cylindrical coordinates
- t - Spacing of piles in number of diameter of pile
- t' - Thickness of diaphragm of pressure cell
- u - Vertical displacement in R-direction for axially symmetric case due to point loading
- v - Vertical displacement in φ -direction for axially symmetric case due to point loading
- z - Vertical distance of a point from the surface
- α - Angle between the external faces of the bearing volume of soil and the lateral surface of the pile
- $\gamma_{R\varphi}, \gamma_{R\psi}, \gamma_{\varphi\psi}$ - Unit shear strains in spherical coordinates
- δ - Central deflection of diaphragm of pressure cell
- $\epsilon_1, \epsilon_2, \epsilon_3$ - Principal strains in spherical coordinates
- ϵ_i - $(\frac{\sigma_i}{c})^n$
- ϵ_i - $\frac{1}{\sqrt{2}} \frac{m}{(m+1)} [(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2]^{\frac{1}{2}}$
- ϵ_R - Unit elongation in R-direction in spherical coordinates

- η - Group efficiency of pile group
 μ - Poisson's ratio ($\frac{1}{m}$)
 ρ_z - Vertical displacement due to point loading
 ρ_{zLCU} - Vertical displacement below the centre of a uniformly loaded circular area for linear case
 ρ_{zLRU} - Vertical displacement under the corner of a uniformly loaded rectangular area for linear case
 ρ_{zNGU} - Vertical displacement below the centre of a uniformly loaded circular area for non-linear cases
 ρ_{zVCP} - Vertical displacement below the centre of a circular area with parabolic loading considering variable modulus of elasticity
 ρ_{zVCU} - Vertical displacement below the centre of a uniformly loaded circular area for variable modulus of elasticity
 ρ_{zVRU} - Vertical displacement under the centre of a uniformly loaded rectangular area for variable modulus of elasticity
 $\sigma_1, \sigma_2, \sigma_3$ - Principal stresses in spherical coordinates
 σ_p - Ultimate unit stress of soil under the pile point
 $\sigma_R, \sigma_\phi, \sigma_\psi$ - Components of normal stress in spherical coordinates
 $\sigma_r, \sigma_\theta, \sigma_z$ - Components of normal stress in cylindrical coordinates
 σ_z - Vertical normal stress due to point loading
 σ_{zLCU} - Vertical stress under the centre of a uniformly loaded circular area for linear case

- σ_{ZLRU} - Vertical stress under the corner of a uniformly loaded rectangular area for linear case
- σ_{ZNGP} - Vertical stress under the centre of a circular area for parabolic loading for non-linear cases
- σ_{ZNCU} - Vertical stress under the centre of a uniformly loaded circular area for non-linear cases
- σ_{ZNRU} - Vertical stress under the corner of a uniformly loaded rectangular area for non-linear cases
- σ_{ZVCP} - Vertical stress under the centre of a circular area for parabolic loading considering variable modulus of elasticity
- σ_{ZVCU} - Vertical stress under the centre of a uniformly loaded circular area for variable modulus of elasticity
- σ_{ZVRU} - Vertical stress under the corner of a uniformly loaded rectangular area for variable modulus of elasticity
- τ_m - Ultimate unit stress of soil along the pile mantle
- $\tau_{R\phi}, \tau_{R\theta}, \tau_{\phi\psi}$ - Components of shear stress in spherical coordinates
- χ - Frohlich's stress concentration factor.