UNIVERSITI PUTRA MALAYSIA

***DEVELOPMENT OF FINITE ELEMENT MODEL FOR SOIL-STRUCTURE INTERACTION***

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**DOCTOR OF PHILOSOPHY**
**UNIVERSITI PUTRA MALAYSIA**

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# DEVELOPMENT OF FINITE ELEMENT MODEL FOR SOIL-STRUCTURE INTERACTION



**By**

**MOHAMMAD DALILI SHOAEI**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy**

**March 2014**

***Dedicated to:***

*My parents, Simin and Akbar*
*My sister, Maryam*
*and*
*My brothers, Ali and Iman*

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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**Chairman: Professor Bujang Kim Huat, PhD**
**Faculty: Engineering**

The presence of soil in framed-structure analysis has shown great effects on the overall performance of soil-foundation-structure system. One of the important features of Soil-Structure Interaction (SSI) analysis is practical prediction of the ultimate bearing capacity of layered dried soil. In addition, mechanical properties of the soil interfacial behavior between soil and shallow infrastructures have been found influential to the structural behavior. Further to the necessity of an accurate interfacial modeling in the soil-foundation-framed structure system, the analyzed model should be computationally efficient to capture the structural performance by considering soil, footing and structure.

Advances in the computer technology have led to the development of several commercial Finite Element (FE) softwares which are available to all researchers. However, none of them could serve as a comprehensive system to compute the ultimate bearing capacity of soil and its interactive effects on structural elements with an acceptable computational time and effort while considering interfacial behavior between soil and foundation.

Therefore, the current research focuses on first, proposing Artificial Neural Network (ANN) as an advanced method capable of prediction of the ultimate bearing capacity of two-layer soil where water table is low enough so that there is no moisture effect on the failure surface. Secondly, an analytical finite element technique has been developed which is capable of modeling and analyzing soil-framed structure interaction equipped with new elements to accurately capture the different aspects of interaction. Hence, the architected ANN and the FE technique form an analysis system while their functionality is not dependent of each other and each one performs their computational tasks separately.

In order to develop an efficient ANN system, the required algorithm is built through trial and error procedure and then through this process feed-forward network with back-propagation training function is implemented. The training data associated with ultimate bearing capacity of layered soil has been exploited from classical and numerical (FE) methods. For the classical method the well-known equation of Meyerhof for two-layered soil has been employed and a Two-Dimensional Finite

Element Code (2DFEC) equipped with a multi-finite element library capable of soil non-linear analysis is utilized. Results from the FE and classical methods are compared for verification.

In the present study, the SSI analytical model is idealized by the two-node beam element and the eight-node serendipity element. In order to consider interfacial behavior and tackle compatibility problem in modeling of SSI between soil and frame element, the new interface element is developed and the associated constitutive law and finite element model is derived. Then, the special finite element algorithm and computer program (2DSSI) is developed to perform two-dimensional nonlinear SSI analysis by considering interfacial behavior of soil and frame elements. Since different materials are used in the current SSI problem constitutive models are employed to capture both the linear and nonlinear interactive behavior of all the materials i.e. concrete, steel, soil and interface element.

In order to evaluate the accuracy of the developed code (2DSSI), a series of examples have been used as benchmarks to verify the analyses. Furthermore, the accuracy of the program code is also verified through analysis of similar examples in literature and then results are compared with SAP2000 and those available in literature. Comparisons showed acceptable accuracy and reasonable prediction of the analysis.

Results from ANN showed good agreement with the classical method. Therefore, ANN can be used as a powerful tool for prediction of ultimate bearing capacity of layered soil. On the other hand, application of the new interface element in SSI analysis has led to considerable changes and redistribution of induced forces and stresses in the frame elements, footing and soil.

In general, application of interface element can well highlight the influence of soil behavior and its consequent effects on the superstructure. Presence of interface element gave rise to considerable redistribution and variation of structural forces. Depending on the mechanical properties of interface element (thickness and stiffness), geometry of superstructure and type of footing, the conducted analyses showed 3% to 38% degradation of axial forces of columns, 5% to 62% reduction of shear forces of columns, 1% to 87% and 6% to 96% redistribution of column and beam moments respectively compared to the models without the interface element.

Moreover, Moment reversal and increase of values of forces in several structural elements were also remarkable in the considered cases that corresponded to the presence of interface element. Larger thickness of interface element added more flexibility to the combined footing and consequently larger settlement and remarkable variation of foundation moment were obtained. All the redistributions and alterations of structural forces contributed in changing the yielding mechanisms of the considered frames. Results revealed that inclusion of interaction between soil and footing along with additional interface element can cause redesign of structural members so the cost of construction may change. Nonlinear interactive analysis of an asymmetric frame in the current study showed 26% increase in the required volume of reinforced concrete for construction of the frame.

The developed system, discussed above, includes an ANN algorithm to predict ultimate bearing capacity of two-layer soil and a finite element model (2DSSI) for analysis of interaction between soil and framed structures through utilization of the developed interface element along with all included aspects of SSI.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia Sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PEMBANGUNAN MODEL ELEMEN TERHAD UNTUK INTERAKSI TANAH-STRUKTUR**

Oleh

**MOHAMMAD DALILI SHOAEI**

**Mac 2014**

**Pengerusi: Professor Bujang Kim Huat, PhD**
**Fakulti: Kejuruteraan**

Kehadiran tanah dalam analisis struktur berangka memberikan kesan yang mendalam ke atas prestasi sistem tanah-asas-struktur. Salah satu ciri penting dalam analisis interaksi tanah-struktur (SSI) ialah ramalan praktikal keupayaan menanggung mutlak tanah berlapis. Tambahan lagi, sifat-sifat mekanikal kelakuan antara-muka tanah antara tanah dan struktur cetek telah didapati mempengaruhi kelakuan struktur. Untuk memastikan pemodelan antara-muka sistem tanah-asas-struktur berangka adalah tepat, model yang dianalisa perlu cekap dari segi penkomputeran untuk mendapatkan prestasi struktur dengan mempertimbangkan tanah, kedudukan dan struktur.

Kemajuan dalam teknologi komputer telah membawa kepada pembangunan beberapa perisian elemen terhad (FE) komersil yang boleh diperolehi para penyelidik. Walau bagaimanapun, tidak ada perisian yang berupaya bertindak sebagai sistem menyeluruh yang boleh mengira keupayaan menanggung mutlak tanah dan kesan interaksinya pada elemen struktur dengan masa pengiraan dan kesukaran yang boleh diterima dan pada masa yang sama mempertimbangkan kelakuan antara-muka antara tanah dan asas.

Oleh itu, terdahulunya penyelidikan ini memberi tumpuan kepadacadangan rangkaian neural tiruan (ANN) sebagai kaedah maju yang mampu meramal keupayaan menanggung mutlak tanah berlapis dua dengan tepat, di mana permukaan air bawah tanah cukup rendah dan tidak memberi kesan kelembapan terhadap permukaan kegagalan. Setelah itu, teknik analisis FE telah dihasilkan yang berupaya untuk memodelkan dan menganalisa interaksi tanah-struktur berangka dan dilengkapi dengan elemen-elemen baru untuk mendapatkan pelbagai aspek interaksi dengan tepat. Dengan itu, ANN yang dibina dan teknik FE menghasilkan satu sistem analisis di mana fungsi setiap satu tidak bergantung antara satu sama lain dan masing-masing menjalankan tugas-tugas pengiraan komputasi secara berasingan.

Dalam usaha membangunkan satu sistem ANN yang cekap, algoritma yang diperlukan dibina melalui prosedur percubaan berulangan dan kemudian melalui proses ini rangkaian ‘feed-forward’ dengan fungsi latihan ‘back-propagation’ dilaksanakan. Data latihan yang berkaitan dengan keupayaan menanggung mutlak

tanah berlapis telah didapati daripada kaedah klasikal dan bernombor (FE). Bagi kaedah klasikal, persamaan Meyerhof yang terkenal untuk tanah dua lapis telah digunakan dan kod elemen terhad dua-dimensi (2DFEC) yang dilengkapi dengan perpustakaan elemen pelbagai-terhad yang mampu menjalankan analisa bukan linear tanah digunakan. Keputusan daripada kaedah FE dan kaedah klasikal telah dibanding untuk pengesahan.

Dalam kajian ini, model analisis SSI disempurnakan dengan elemen-elemen 'two-node beam' dan 'eight-node serendipity'. Bagi mempertimbangkan kelakuan antara-muka dan menyelesaikan masalah keserasian dalam pemodelan SSI antara tanah dan elemen rangka, elemen antara-muka yang baru dihasilkan dan hukum juzuk yang berkaitan dan model elemen terhad didapatkan. Selepas itu, algoritma elemen terhad yang khas dan program komputer (2DSSI) dihasilkan untuk melaksanakan analisis bukan linear SSI dua dimensi dengan mempertimbangkan kelakuan antara-muka tanah dan elemen rangka. Oleh sebab bahan yang berlainan digunakan dalam SSI pada masa kini, model-model juzuk digunakan untuk mendapatkan kedua-dua kelakuan interaktif linear dan bukan linear untuk semua bahan seperti konkrit, keluli, tanah dan elemen antara-muka.

Dalam usaha untuk menilai ketepatan kod yang dihasilkan (2DSSI), satu siri contoh telah digunakan sebagai piawaian untuk pengesahan analisis. Tambahan pula, ketepatan kod ini juga disahkan melalui analisis contoh-contoh yang serupa dalam litratur dan kemudian keputusan dibandingkan dengan SAP2000 dan maklumat yang didapati daripada litratur. Perbandingan menunjukkan ketepatan dan ramalan analisis yang memuaskan.

Keputusan daripada ANN adalah bersetujuan dengan kaedah klasikal. Oleh itu, ANN boleh digunakan sebagai peralatan yang berkesan untuk meramal keupayaan menanggung mutlak tanah berlapis. Penggunaan elemen antara-muka baru dalam analisis SSI telah membawa kepada perubahan ketara dan pengagihan semula beban dikenakan dan tekanan dalam elemen rangka, kedudukan dan tanah. Secara umumnya, penggunaan elemen antara-muka dapat menekankan pengaruh tingkah laku tanah dan kesan akibatnya kepada 'superstructure'.

Secara umum, aplikasi unsur antara muka boleh menyerlahkan pengaruh tingkah laku tanah dan kesannya terhadap 'superstructure'. Kehadiran unsur antara muka menyebabkan pengagihan semula dan perubahan daya struktur yang ketara. Bergantung kepada ciri-ciri mekanikal unsur antara muka (ketebalan dan kekerasan), geometri 'superstructure' dan jenis asas, analisis yang dijalankan menunjukkan 3% sehingga 38% degradasi daya paksi, 5% sehingga 62% pengurangan daya ricih tiang, 1% sehingga 87% dan 6% sehingga 96% pengagihan semula 'moment' tiang dan alang, masing-masing berbanding dengan model tanpa unsur antara muka.

Selain itu, pembalikan 'moment' dan peningkatan nilai-nilai daya dalam beberapa unsur struktur didapati ketara dalam kes-kes dikaji yang mempunyai unsur antara muka. Ketebalan unsur antara muka yang lebih besar menambahkan fleksibiliti kepada gabungan asas dan menyebabkan penempatan yang lebih besar dan perubahan ketara 'moment' dasar diperolehi. Semua pengagihan dan perubahan daya struktur menyumbang kepada perubahan dalam mekanisma kelenturan dalam rangka-rangka yang dikaji. Hasil kajian menunjukkan bahawa kemasukan interaksi antara tanah dan asas bersama dengan tambahan unsur antara muka boleh menyebabkan perubahan dalam reka bentuk bahagian-bahagian struktur yang mungkin memberi kesan terhadap kos pembinaan. Analisis interaktif 'nonlinear' rangka tidak bersimetri dalam kajian ini menunjukkan peningkatan sebanyak 26% dalam isipadu konkrit bertetulang yang diperlukan untuk pembinaan rangka.

Sistem yang dihasilkan tersebut mengandungi algoritma ANN untuk meramal keupayaan menanggung mutlak tanah dua lapis dan satu model elemen terhad (2DSSI), kecekapan analisa interaksi antara tanah dan struktur berangka ditunjukkan melalui penggunaan elemen antara-muka yang dihasilkan dengan mempertimbangkan kesemua aspek SSI.

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## APPROVAL

I certify that a Thesis Examination Committee has met on 12th March 2014 to conduct the final examination of Mohammad Dalili Shoaei on his thesis entitled "Development of finite element model for soil-structure interaction" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the supervisory Committee were as follows:

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