Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Correlation between RC fiber section model and shallow foundation model

S. Limkatanyu, W. Prachasaree & P. Chaiviriyawong

Department of Civil Engineering, Faculty of Engineering, Prince of Songkla University, Thaialnd.

M. Kwon

Department of Civil Engineering, Gyeongsang National University, South Korea.

ABSTRACT: Due to growing interests in the Performance-Based Seismic Design and Assessment Methodology, more realistic modelling of a structural system is crucial in analyzing, designing, and evaluating both newly constructed and existing buildings under earthquake excitation. Therefore, a shallow foundation element serves as an essential element in the implementation of this seismic design and assessment methodology. In this work, a contact interface fiber section element is proposed for use in modelling soil-shallow foundation systems. The hypothesis of a rigid footing on a Winkler-based soil simply relies on the Euler-Bernoulli's hypothesis on sectional kinematics. Fiber-section model is employed to represent the contact interface sectional response. The hyperbolic function offers an adequate means of modelling the stress-deformation behavior of each soil fiber. The proposed element is simple but efficient in accounting for dominant features of the soil-shallow foundation system. Experimental results from centrifuge-scale and full-scale cyclic loading tests on shallow foundations are used to show the model characteristics and verify the accuracy of the model. Based on this comprehensive model validation, it is concluded that the model performs quite satisfactorily. It can capture reasonably well the experimental results in terms of moment, shear, settlement, and rotation demands. The hysteretic characteristic of moment-rotation responses and the rotation-settlement feature are also captured well by the model.

.

1 INTRODUCTION

The interactive mechanism between a shallow foundation and its contacting soils has become an essential element in analyzing, designing, and evaluating both newly constructed and existing buildings under earthquake excitations. This is particularly important when the Performance-Based Seismic Design and Assessment Methodology (SEAOC. Vision 2000, 1995) is adopted. In general, there are two sophisticated nonlinear phenomena associated with the soil-structure interactive mechanism, namely: material nonlinearity and geometric nonlinearity. The former results from yielding of the contacting soils as well as gap formation at soil-foundation interfaces while the latter is caused by the foundation uplift. These two nonlinear mechanisms cause shallow foundations to slide, settle, and rock under earthquake excitations (Yang et al. 2000). As a result, the nonlinear shallow foundation model capable of accounting for both nonlinear mechanisms is an essential constituent in executions of the recently adopted Performance-Based Seismic Design and Assessment Methodology.

Several numerical models with different degrees of sophistication have been proposed in the research community to account for the interaction mechanisms between the soil-structure interactive mechanism, namely (*a*) continuum finite element model (Huat and Mohammed, 2006); (*b*) discrete Winkler-based spring model (Raychowdhury, 2008); and (*c*) macro-element model (Chatzigogos et al., 2011). The pros and cons of these three numerical models are briefly discussed in Limkatanyu et al. (2012).

The main objective of this paper is to present a simplified but efficient contact interface element for modeling soil-shallow foundation systems proposed by Limkatanyu et al. (2012). The contact interface constitutive model is based on the fiber-section discretization model (Spacone et al., 1994) in which each fiber in the fiber-section model represents the contacting soil. The hypothesis of a rigid footing on the Winkler-based soil resembles the Euler-Bernoulli's hypothesis on sectional kinematics. Two correlation studies between experimental and numerical models are employed to show the model characteristics and assess the model accuracy. All dominant interaction mechanisms (settling, uplifting, rocking, and sliding) are captured reasonably well by the proposed model. The general-purpose finite element program FEAP (Taylor, 2000) is used to host the proposed element.

2 CONTACT INTERFACE FIBER SECTION (CIFS) ELEMENT

2.1 Definition

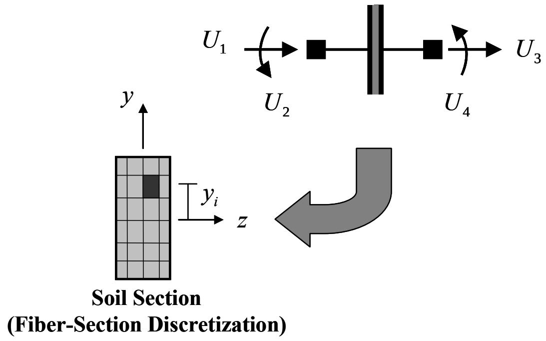

Figure 1: Contact Interface Fiber Section (CIFS) Element

Figure 1 shows the contact interface fiber section (CIFS) element proposed by Limkatanyu et al. (2012). The element consists of two nodes connected by a zero-length contact interface section. The zero-length contact interface section is employed to model the soil-structure interactive mechanism. The element nodal displacements are grouped as:

$$\mathbf{U} = \left\{ \mathbf{U}^1 \;\vdots\; \mathbf{U}^2 \right\}^T \tag{1}$$

where $\mathbf{U}^1 = \left\{ U_1 \quad U_2 \right\}^T$ and $\mathbf{U}^2 = \left\{ U_3 \quad U_4 \right\}^T$ are arrays collecting the displacements at nodes 1 and 2, respectively. Their work-conjugate nodal forces are grouped in the element force vector $\mathbf{P} = \left\{ \mathbf{P}^1 \;\vdots\; \mathbf{P}^2 \right\}^T$. The contact interface sectional deformations are axial deformation u and transverse rotation θ and are grouped as:

$$\mathbf{d} = \left\{ u \quad \theta \right\}^T \tag{2}$$

The associated contact interface sectional forces **D** are:

$$\mathbf{D} = \left\{ N \quad M \right\}^T \tag{3}$$

where N and M are the axial force and the bending moment, respectively.

2.2 Compatibility

The contact interface sectional deformations **d** can be written in terms of the element nodal displacements **U** as:

$$\mathbf{d} = \mathbf{\Gamma}_{RBM} \;\mathbf{U} \tag{4}$$

where $\mathbf{\Gamma}_{RBM}$ is the rigid-body mode transformation matrix and is given in Limkatanyu et al. (2012).

2.3 Contact interface constitutive laws: fiber-section discretization

In this paper, the fiber section model with nonlinear uniaxial stress-deformation laws for the contacting soil is used to derive and linearize the nonlinear relation between the contact interface sectional forces **D** and deformations **d** as:

$$\mathbf{D} = \mathbf{D}^0 + \mathbf{k}\Delta\mathbf{d}^0 \quad (5)$$

where $\mathbf{D}^0$ and $\mathbf{d}^0$ are the initial contact interface section forces and deformations, respectively; and **k** is the contact interface section stiffness. More details on the contact interface fiber-section constitutive model can be found in Limkatanyu et al. (2012).

2.4 Equilibrium: the virtual displacement principle

The equilibrium relation between the contact interface forces **D** and the element nodal forces **P** can be derived using the virtual work principle. Employing Eq. (4) and subsequently enforcing the arbitrariness of the virtual nodal displacements $\delta\mathbf{U}$ lead to:

$$\mathbf{\Gamma}_{RBM}^{T} \; \mathbf{D} = \mathbf{P} \quad (6)$$

Substitution of Eqs. (5) into (6) results in the incremental form of equilibrium as:

$$\mathbf{K}\Delta\mathbf{U} = \mathbf{P} - \mathbf{P}^0 \quad (7)$$

where $\mathbf{K} = \mathbf{\Gamma}_{RBM}^{T}\mathbf{k}\mathbf{\Gamma}_{RBM}$ is the shallow foundation element stiffness matrix; and $\mathbf{P}^0 = \mathbf{\Gamma}_{RBM}^{T}\mathbf{D}^0$ is the element resistant force vector.

3 CONTACT INTERFACE SECTIONAL CONSTITUTIVE LAWS

In this paper, the contact interface fiber section element is employed to represent three interactive modes between shallow foundations and surrounding soils, namely: sliding, settling, and rocking. The vertical bearing response of underlying soils is required to model the settling and rocking interaction modes and is represented by the so-called "*q-z* element". The shear-friction response of surrounding soils is needed to represent the sliding interaction mode and is modeled by the so-called "*t-x* element". Constitutive laws of surrounding soils for the *q-z* and *t-x* elements are described as follows:

3.1 Vertical bearing response of underlying soils: *q-z* curve

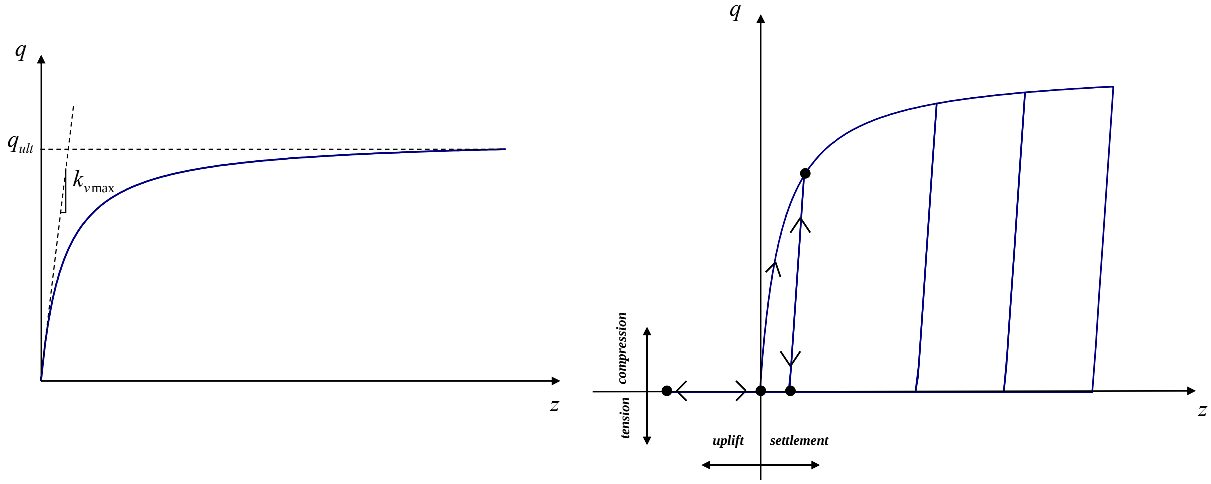

Figure 2: Hyperbolic *q-z* Model (Derivative from Limkatanyu et al., 2012)

In this paper, a set of 1-D springs continuously distributed within the footing area are used to model the soils underneath a footing. The so-called "*q-z* curve" is employed to characterize these 1-D soil springs. The ultimate vertical bearing capacity q_{ult} is computed using the formula proposed by Meyerhof (1963) since it is widely used by geotechnical engineers (Cernica, 1995).

A general hyperbolic equation proposed by Duncan and Chang (1970) is employed to represent the monotonic response between the bearing soil pressure q and soil settlement z as shown in Figure 2 (a). A schematic representation of the hysteretic *q-z* curve is shown in Figure 2 (b). More details on this q-z model are presented in Limkatanyu et al. (2012).

3.2 Frictional resistant response of underlying soil-footing interfaces: *t-z* curve

In this paper, the frictional sliding resistance along the underlying soil-footing interface is represented by 1-D springs distributed within the contact interface section. The so-called "t-x curve" is used to characterize these 1-D interface springs. The ultimate sliding shear strength t_{ult} is computed based on the classical Mohr-Coulomb failure criteria as:

$$t_{ult} = \frac{W_{structure}}{A_{footing}} \tan\delta + c \tag{8}$$

where $W_{structure}$ is the structural weight transferred to the considered footing; $A_{footing}$ is the footing surface area; and δ is the frictional angle between the underlying soil-footing interfaces. The elastic-perfectly plastic hysteretic model is used to characterize the cyclic response of the t-x curve as shown in Figure 3. More details on this t-x model are presented in Limkatanyu et al. (2012).

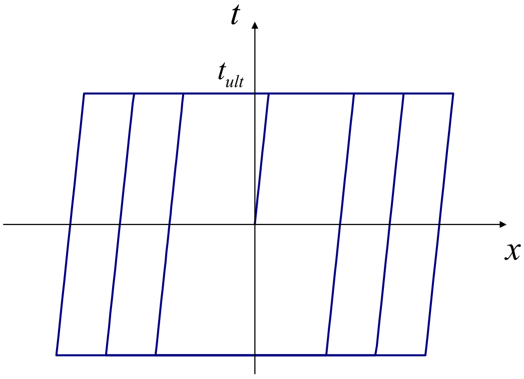

Figure 3: Hysteretic t-x Model (Derivative from Limkatanyu et al., 2012)

4 CORRELATION STUDIES BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

4.1 UC-Davis centrifuge experiment: KKR-03

A series of centrifugal tests at UC-Davis are conducted to study the nonlinear response of shearwall strip footings under vertical push, lateral cyclic loadings, and base excitations (Rosebrook, 2001). In this paper, the experimental results from the so-called KKR-03 model are selected to validate the proposed shallow foundation model. Figure 4 shows the centrifuge test setup for KKR-03 model under lateral cyclic loadings. More details on the test setup and system properties can be found in Limkatanyu et al. (2012).

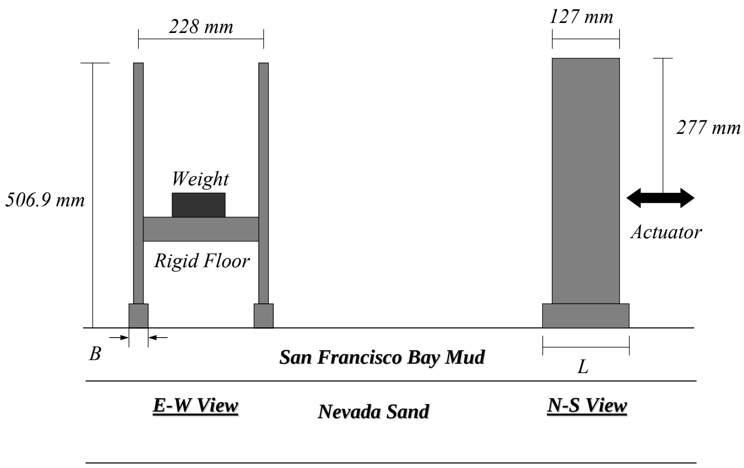

Figure 4: Test Setup of KKR-03 Model (After Gajan, 2006)

Correlation studies between experimental and numerical results are shown in Figures 5 through 7.

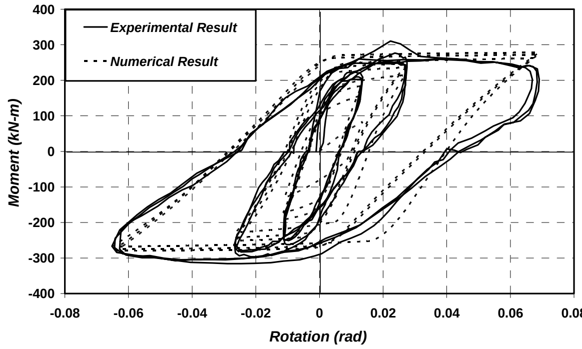

Figure 5: Moment-Rotation Responses: Experimental and Numerical Results

(Derivative from Limkatanyu et al., 2012)

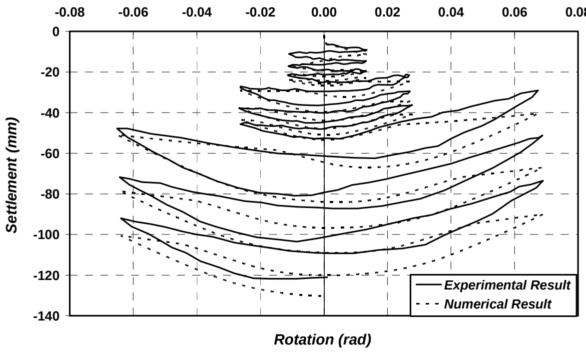

Figure 6: Settlement-Rotation Responses: Experimental and Numerical Results

(Derivative from Limkatanyu et al., 2012)

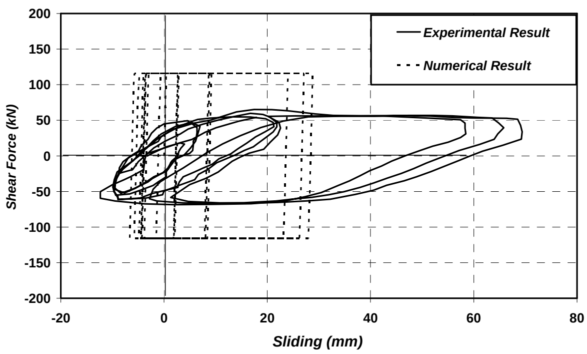

Figure 7: Frictional Shear-Sliding Displacement Responses: Experimental and Numerical Results

(Derivative from Limkatanyu et al., 2012)

Comparison between experimental and numerical moment-rotation responses is shown in Figure 5. In general, it can be observed that the proposed CIFS model can represent well the dominant features of the experimental moment-rotation response, namely: the moment capacity, stiffness degradation with increasing rotational amplitude, amount of dissipated hysteretic energy, and general shape of hysteretic response. More details on the correlation studies between experimental and numerical moment-rotation responses can be found in Limkatanyu et al. (2012).

Figure 6 compares the experimental and numerical settlement-rotation responses and indicates that they both illustrate the sinking dominated foundation responses. Furthermore, Figure 6 also shows that the proposed model can present well the evolution of settlement history and the final value of settlement. Due to the fact that the static vertical factor of safety ($FS_V \approx 2.8$) is comparatively small in the KKR-03 model, the accumulated permanent settlement for each loading cycle is clearly noticed both in experimental and numerical results. More details on the correlation studies between experimental and numerical settlement-rotation responses can be found in Limkatanyu et al. (2012). Comparison between experimental and numerical horizontal shear-sliding displacement responses are shown in Figure 7. Unfortunately, the proposed *t-x* contact interface element poorly resembles the experimental result. However, the decent aspect of this correlation is that the amount of dissipated hysteretic energy is reasonably well predicted by the numerical model. More details on the correlation studies between experimental and numerical horizontal shear-sliding displacement responses can be found in Limkatanyu et al. (2012).

4.2 **TRISEE 1-g experiment: HD test**

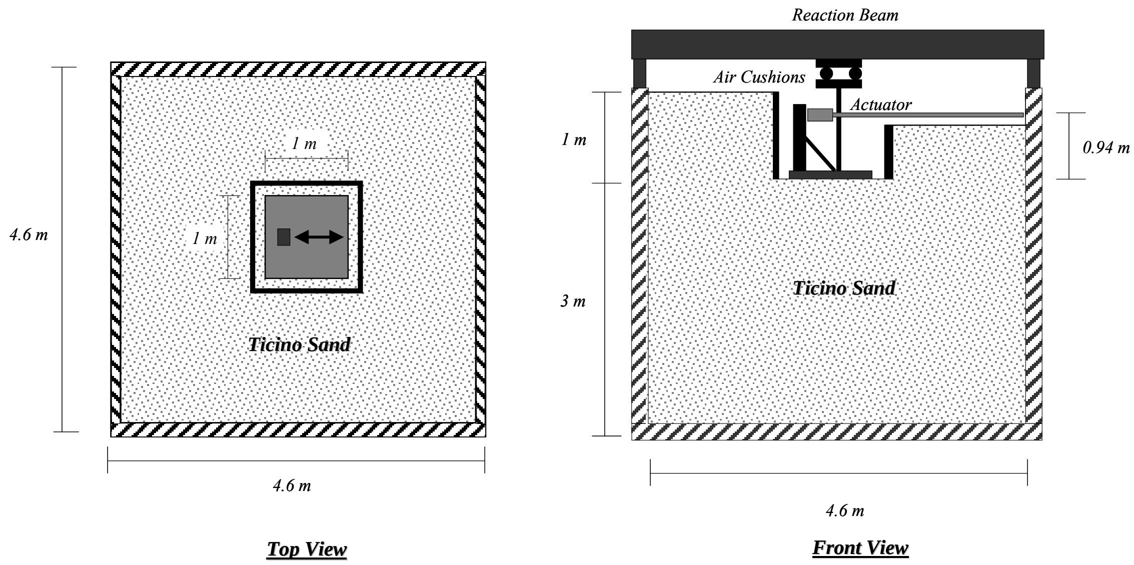

Figure 8: TRISEE Experimental Setup (After Negro et al., 1998)

As a part of the research project TRISEE (3D site Effects of Soil-Foundation Interaction in Earthquake and Vibration Risk Evaluation), large scale experiments on a shallow foundation subjected to static vertical, lateral cyclic, and dynamic loadings were performed at the ELSA laboratory in Italy. A test setup of TRISEE program is shown in Figure 8. More details on the test setup and system properties can be found in Limkatanyu et al. (2012).

Figures 9 through 11 show correlation studies between experimental and numerical models. Figure 9 shows comparison between experimental and numerical moment-rotation responses and indicates that the moment capacity is well predicted by the numerical model while an amount of dissipated hysteretic energy is underestimated. Also it can be observed that general features of the experimental moment-rotation response are presented well by the proposed numerical model within acceptable engineering tolerance.The model ability to capture the *S*-shaped moment-rotation response can clearly observed in Figure 9. The numerical settlement-rotation response is shown in Figure 10. The uplifting dominated foundation response is clearly noticed by the *U*-shaped settlement-rotation response ($FS_V \approx 5$). The accumulation of permanent settlement for each loading cycle can be observed but it is not as severe as in the case of KKR-03 experiment (the sinking dominated response). Comparison between experimental and numerical horizontal shear-sliding displacement responses are shown in Figure 11. Inconsistencies between experimental and numerical results are mainly due to the uncoupling response between the vertical bearing pressure and horizontal sliding shear as well as a large value of initial stiffness used to emulate the rigid-plastic behavior. However, the decent aspect of this comparison is that the amount of dissipated hysteretic energy is well predicted by the numerical model.

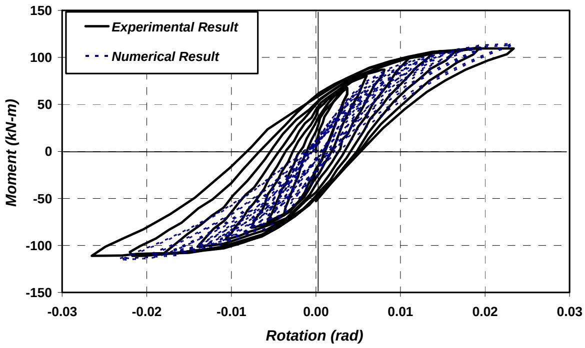

Figure 9: Moment-Rotation Responses: Experimental and Numerical Results

(Derivative from Limkatanyu et al., 2012)

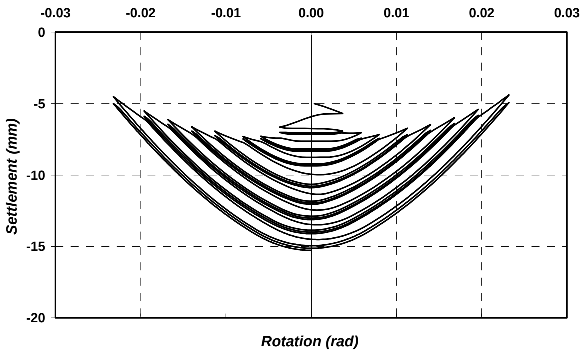

Figure 10: Numerical Settlement-Rotation Response (Derivative from Limkatanyu et al., 2012)

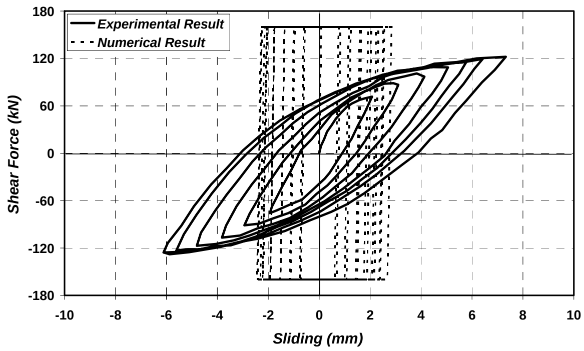

Figure 11: Frictional Shear-Sliding Displacement Responses: Experimental and Numerical Results

(Derivative from Limkatanyu et al., 2012)

5 SUMMARY AND CONCLUSIONS

A simplified but efficient contact interface element for modeling a soil-shallow foundation system is discussed in this paper. The contact interface sectional response stems from the fiber-section discretization widely used in describing sectional responses of reinforced concrete and steel members. The soil-foundation interactive mechanisms (sliding, settling, and rocking) can reasonably well be modelled by the proposed element. The element accuracy is thoroughly validated against several experimental studies including centrifuge-scale as well as large-scale experiments. In case of the sinking-dominated foundation (UC-Davis experiment), the proposed element is successful in capturing the moment capacity, general shape of hysteretic moment-rotation response, and settlement-rotation evolution. In case of the rocking-dominated foundation (TRISEE experiment), the proposed element shows its capability of predicting the moment capacity and characterize the *S*-shaped moment-rotation as well as *U*-shaped settlement-rotation responses while an amount of dissipated hysteretic energy is underestimated.

The formulation of the proposed shallow foundation element is an essential step forward in setting up a computational framework that allows full nonlinear static and dynamic analyses of frame structures accounting for the soil-shallow foundation interactive effects. Both beneficial and detrimental effects own to this interactive mechanism are necessarily included in the numerical model. Therefore, the development of the nonlinear shallow foundation element is a crucial step toward implementation of the newly adopted Performance-Based Seismic Design and Assessment Methodology.

REFERENCES:

Cernica J.N. 1995. *Foundation Design*, John Wiley & Sons Inc., New York.

Chatzigogos C.T., Figini R., Pecker A., and Salencon J. 2011. A macro-element formulation for shallow foundations on cohesive and frictional soils. *International Journal for Numerical and Analytical Methods in Geomechanics*. 35. 902-935.

Duncan J.M. and Chang C.Y. 1970. Nonlinear analysis of stress and strain in soils. *Journal of* the *Soil Mechanics* and Foundations Division. 96(5). 1629-1653.

Gajan S. 2006. Physical and Numerical Modeling of Nonlinear Cyclic Load-Deformation Behavior of Shallow Foundations Supporting Rocking Shear Walls , Doctoral Thesis, Department of Civil and Environmental Engineering, University of California, Davis.

Huat B.B.K. and Mohammed T.A. 2006. Finite element study using FE code (PLAXIS) on the geotechnical behavior of shell footings. *Journal of Computer Science*. 2(1). 104-108.

Limkatanyu S., Kwon M., Prachasaree W., and Chaiviriyawong P. 2012. Contact interface fiber section element: shallow foundation modelling. *Geomechanics and Engineering*. 4(3). 173-190.

Meyerhof G.C. 1963. Some recent research on the bearing capacity of foundations, *Canadian Geotechnical Journal*. 1(1), 16-26.

Negro P., Verzeletti G., Molina J., Pedretti S., Lo Presti D., and Pedroni S. 1998. *Large Scale Geotechnical Experiments on Soil-Foundation Interaction*, Special Publication No. I.98.73, European Commission Joint Research Centre, Ispra, Italy.

Raychowdhury P. 2008. *Nonlinear Winkler-based shallow foundation model for performance assessment of seismically loaded structures*, Doctoral Thesis, Department of Civil and Environmental Engineering, University of California, San Diego.

Rosebrook K.R. 2001. *Moment Loading on Shallow Foundations: Centrifuge Test Data Archives*, Master Thesis, Department of Civil and Environmental Engineering, University of California, Davis.

SEAOC 1995. Vision 2000: Performance based seismic engineering of buildings, Structural Engineers Association of California, Sacramento, CA.

Spacone E., Filippou F.C., and Taucer F.F. 1994. Fibre beam-column model for nonlinear analysis of R/C frames: part I- formulation. *Earthquake Engineering* and *Structural Dynamics.* 25. 711-725.

Taylor R.L. 2000. *FEAP: A Finite Element Analysis Program. User manual: version 7.3*, Department of Civil and Environmental Engineering, University of California, Berkeley.

Yang Y.B., Hung H.H., and He M.J. 2000. Sliding and rocking response of rigid blocks due to horizontal excitations. *Structural Engineering and Mechanics.* 9(1). 1-16.