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Modelling the behaviour of shallow foundation using Beam on Nonlinear Winkler Foundation

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ABSTRACT: Performance-based design (PBD) provides an efficient, economical and robust design procedure to target specific levels of performance expected from engineered systems. The PBD will realize its full potential, if sufficient data on the expected seismic performance of structural systems and its components, foundations and supporting soil types are available. Observations from past earthquakes suggest that buildings on shallow foundations can perform well during strong earthquakes. In this study, the Beam on Nonlinear Winkler Foundation (BNWF) is used to model the soil nonlinearity. The response of a shallow foundation founded on dense sand, modelled using BNWF model is considered. The finite element results of the response of the foundation are validated using centrifuge test results. As part of the study, rotation, settlement, sliding, moment and shear force are evaluated at the base of the footing. The BNWF model predicted all the responses fairly well in comparison with the centrifuge results.

1 INTRODUCTION

Earthquakes cause huge losses to mankind and its environment. The amount of damage caused during earthquakes depends on the preparedness to withstand the effects of the seismic activity. Structural design for earthquake considerations has evolved over a period of time and continued to do so. Every advancement in structural and seismic design is attributed to the new knowledge provided by the ongoing research activities. Performance-based design (PBD) concepts have become increasingly popular among modern designers. The PBD ensures that the building can perform its intended function satisfactorily under anticipated seismic loading with an acceptable level of accuracy as specified by the designer. The PBD aims to satisfy the structure-specific performance requirements rather than ensuring that the response is within the certain prescribed limits. Recently, the PBD concepts are being used in geotechnical engineering (e.g. Iai and Tobita 2010, Gunay and Mosalam 2013, Kramer 2014) to provide improved designs to avoid the conservativeness present in the conventional design approaches. The complete implementation of the PBD approach in geotechnical engineering requires robust data related to seismic performance of different configurations of the soil-foundation-structure systems and its non-structural components along with a better ground motion prediction model for any ground conditions. The design of shallow foundation system is mostly based on code-based prescriptions. These prescriptions are mostly based on experience and empirical knowledge.

In the design of shallow foundations, the foundation is assumed to have failed if the bearing failure is observed. However, the observations from post-earthquakes as documented by researchers (Pender and Robertson 1987, Butcher et al. 1998, Ulusay et al. 2002, Toh and Pender 2008) suggest that the shallow foundations located near to the fault-induced ground rupture have responded exceptionally well. The damage to the foundation and associated structures were observed to be minimal. The above fact suggests that the shallow foundation designed based on code based prescriptions are too conservative. The structure supported on shallow foundation subjected earthquake ground motion may undergo settlement, sliding and rocking. These movements during seismic excitation are not only unavoidable, but may even be beneficial if they are under control (Gajan et al. 2003, 2008). Underestimation of the beneficial effects of these movements prohibits the use of nonlinear energy dissipation in seismic protection of superstructure especially when the ground motion exceeds the design limit. The existing soil models are either too complex or not capable of accurately modelling the soil nonlinearity. Over the years, a few studies have been conducted to model the behaviour of structures supported on shallow foundations using Winkler based approach. Raychowdhary (2008) proposed a Beam on Nonlinear Winkler Foundation (BNWF) approach for modelling the seismic response of shallow foundation. The BNWF model can account for the behaviour of soil-foundation system due to nonlinear and inelastic soil behaviour. The model comprises of system of closely spaced independent, nonlinear springs for modelling settlement, sliding and rotational behaviour along with dashpot and gap elements to model the energy dissipation and gapping respectively. The BNWF model is relatively simple, requires minimal computational effort and well suited for soil-structure interaction (SSI). In the present study, an attempt is made to model the behaviour of structure supported on shallow foundation using the BNWF model to assess the aforementioned benefits of considering the nonlinear soil-structure interaction. The response analysis of the strip footing is performed in OpenSees platform. The OpenSees is a finite element program created at Pacific Earthquake Engineering (PEER) center for simulating the response of structural and geotechnical systems subjected to earthquakes. The finite element results of the response of the footing are validated using centrifuge test results.

2 MODELLING SEISMIC RESPONSE OF SHALLOW FOUNDATION

2.1 *BNWF model*

The response of shallow foundation i.e. strip footing is modelled using the BNWF model. The model consists of elastic beam-column elements to capture the structural footing behaviour and zero-length soil elements to model the soil-footing interaction. The model is developed for two-dimensional analysis representing the nonlinear inelastic behaviour of the soil using modified versions of QzSimple1, PySimple1 and TzSimple1 material models in the OpenSees (Boulanger et al. 1999, Boulanger 2000a, b, c). Figure 1 shows the schematic representation of BNWF model used in the study. The q-z, p-x and t-x springs simulate vertical load-displacement behaviour, horizontal passive load-displacement behaviour and horizontal shear-sliding behaviour respectively.

A typical zero-length element used in the OpenSees is shown in Figure 2. The PySimple1 and QzSimple1 springs can account for soil-foundation separation via gap elements added in series with the elastic and plastic components. The elastic component of the spring can capture

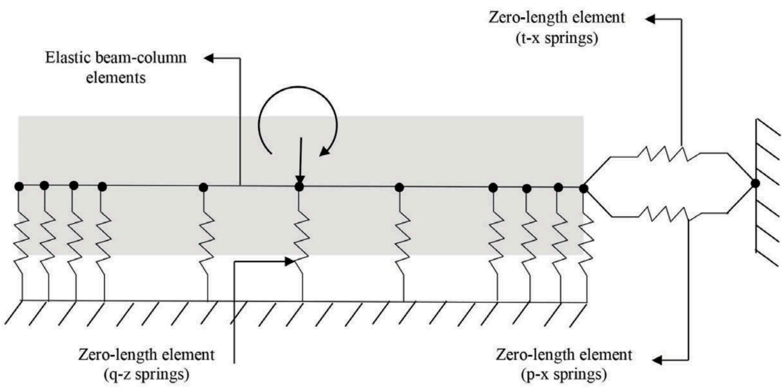

Figure 1. Schematic representation of BNWF model.

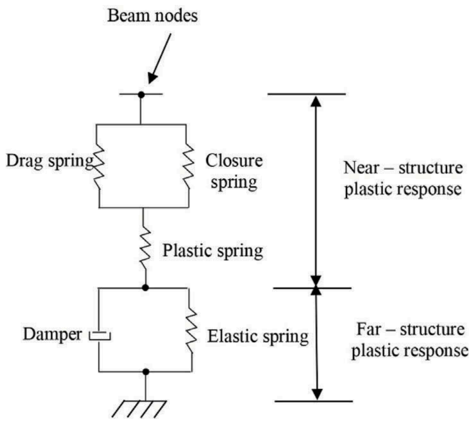

Figure 2. Schematic of zero-length element.

the far-field elastic response, and plastic component captures the near-field plastic response. The zero-length element springs are characterized by a nonlinear backbone curves resembling a bilinear behaviour with a linear and nonlinear regions to represent degrading stiffness as displacement increases. The material models and the parameters that describe these backbone curves defined in OpenSees are based on calibration against the pile load test. In this study, the parameters that describe the backbone curves are selected based on calibration against the shallow foundation load tests data of Raychowdhary & Hutchinson (2008).

2.2 *Details of the centrifuge experiment*

Gajan et al. (2003) conducted a series of centrifuge experiments on shear wall structures with shallow footing. Each test included shear wall-footing models subjected to varying loading conditions. In this study, an experimental case of a model subjected to slow lateral cyclic load is considered. The schematic representation of the test set up is depicted in Figure 3. The figure also shows the instrument locations, which give displacement response of the shear wall-footing system.

The surface resting strip footing dimensions are, width B = 2.8 m and depth D = 0.65 m. The footing is resting on dry sand with a relative density, D_r = 80% and a peak friction angle of 42°. The height of the shear wall is, H = 10.1 m. The shear wall-footing structure was subjected to slow lateral cyclic loading by an actuator during the centrifuge experiment. Four linear potentiometers were fixed at specific locations to measure the displacements of the footing. The centrifuge was spun until the centrifugal acceleration normal to the sand surface was 20g and loading was applied.

2.3 *Finite element modelling of the centrifuge experiment*

The shear wall-footing system tested in the centrifuge is shown schematically with BNWF model in Figure 4, the same is used in finite element analysis using OpenSees program. The elastic beam-column element is used to model the shear wall and footing. The soil-footing interaction is modelled using zero-length elements. The vertical q-z springs are attached to the bottom of the footing (Figure 4). The distribution of vertical springs along the footing width enables the model to capture the moment-rotation behaviour. The ATC-40 (1996) suggests that the stiffer springs should be placed at the end region to account for larger reaction developed at the end of the stiff footing. The variable stiffness distribution along the footing width is modelled by keeping the spring spacing at closer intervals at the end regions and increasing the spacing at the middle region appropriately. The input parameters used in the finite element simulation are given in Table 1.

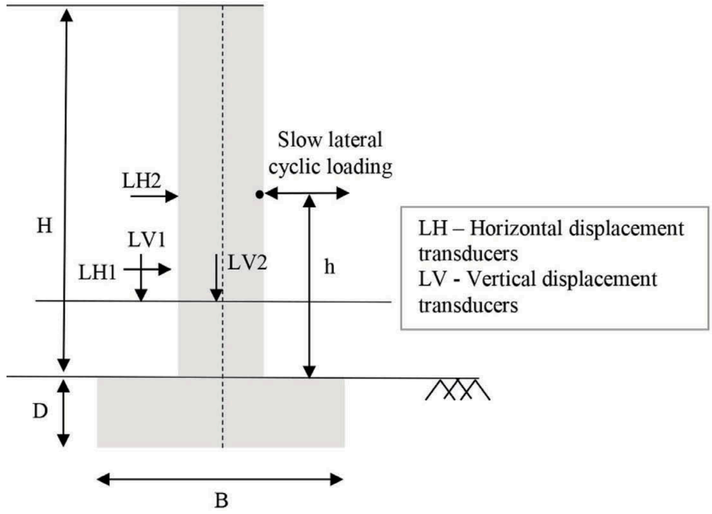

Figure 3. Geometry and instrumentation set up for centrifuge test (Gajan et al., 2003).

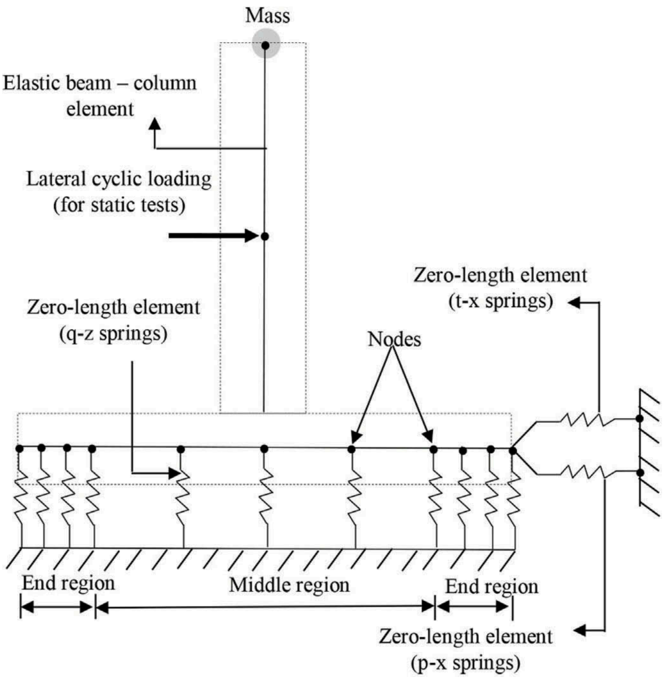

Figure 4. Schematic model geometry of shear wall-footing.

Table 1. Winkler model parameters.

Young's Modulus	Poisson's ratio	End length ratio	Spring spacing at end region	Spring spacing at middle region	Vertical Tension Capacity
(MPa)		(%)	(m)	(m)	(%)
45	0.35	12	0.027	0.106	10

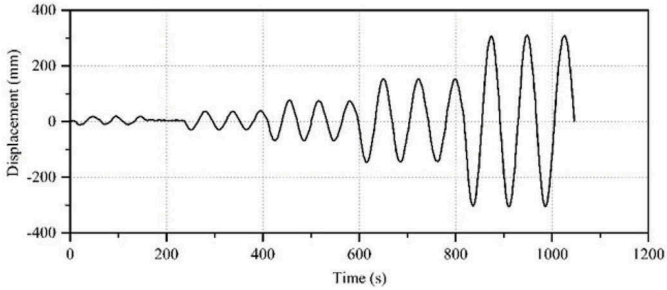

Figure 5. Input displacement time history.

The scale factor used in the centrifuge tests is 20 and the same is used to obtain the finite element model configuration. End length ratio is the ratio of the length of end region to the total length of the footing. The vertical tension capacity (TP) can be taken as 0 – 10% of the compression capacity. In this study, it is taken as 10%. The total number of vertical spring elements are 45 with 13 at each end region and 19 at the middle region of the footing. The total vertical stiffness value is 79.45 MN/m. The individual spring constant is obtained by dividing the total vertical stiffness by number of q-z springs. In the analysis, footing is considered as surface footing without embedment. The shear-sliding behaviour of the footing is simulated using the shear spring and the corresponding spring stiffness is 68.5 MN/m.

Gravity analysis is performed under load control, and the subsequent response analysis is performed under displacement control. In order to predict the damage that a structure undergoes during an earthquake event, it is important to represent in a realistic way the behaviour of structural components during loading reversals. The input displacement time history used in the finite element analysis is shown in Figure 5. This input is obtained from the centrifuge results after multiplying with the scale factor and is applied at the bottom of the footing. The slow rate of loading selected in this study provides an insight into the structural behaviour after the post yielding. Newton algorithm is used in the OpenSees to perform the nonlinear computations needed in the analysis.

3 RESULTS AND DISCUSSION

3.1 *Results*

The prototype-scale shear wall-footing is modelled using BNWF model in OpenSees platform. The response quantities evaluated are rotation, vertical settlement, horizontal displacement, shear force and bending moment at the base center point of the footing. Figures 6 – 11 show the comparison between the results of the OpenSees simulation and centrifuge test results.

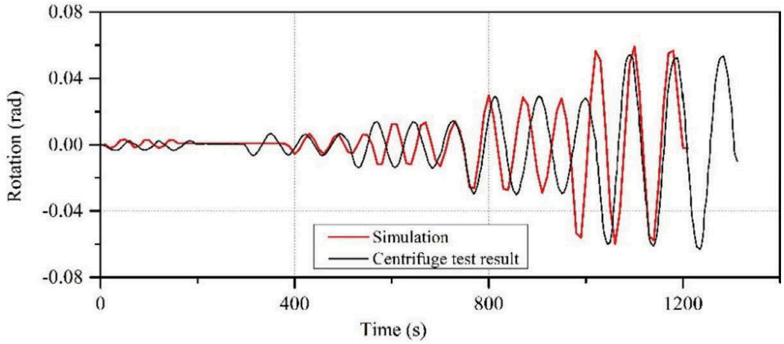

Figure 6. Rotation of the footing at the center of the base.

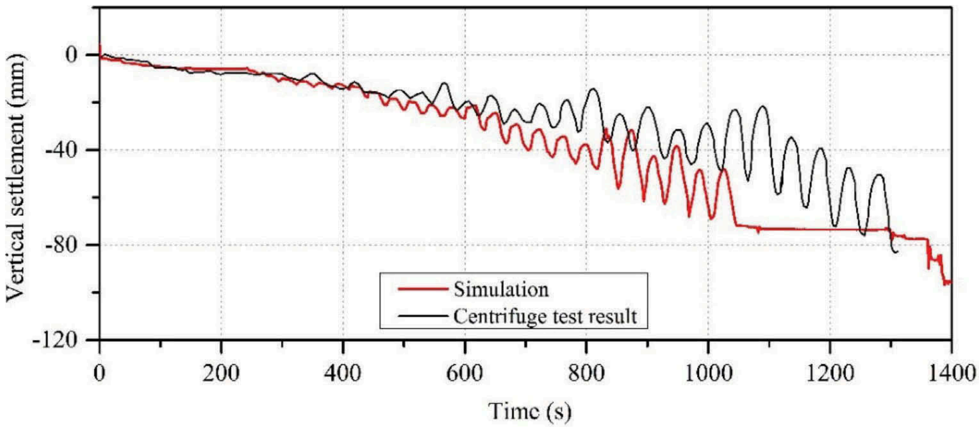

Figure 7. Vertical settlement of the footing at the center of the base

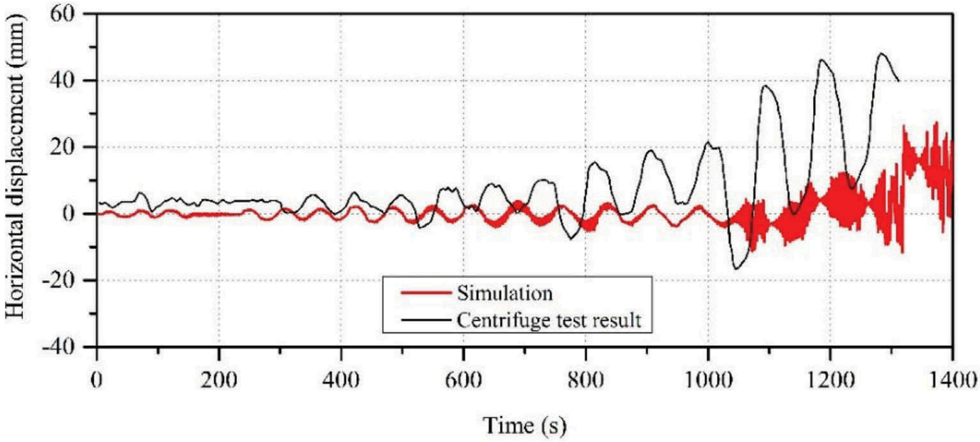

Figure 8. Horizontal displacement of the footing at the center of the base.

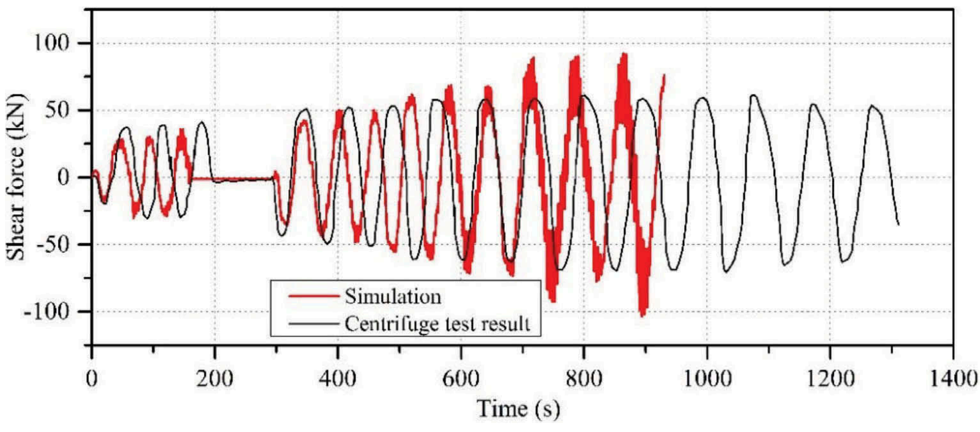

Figure 9. Shear force in the footing at the center of the base.

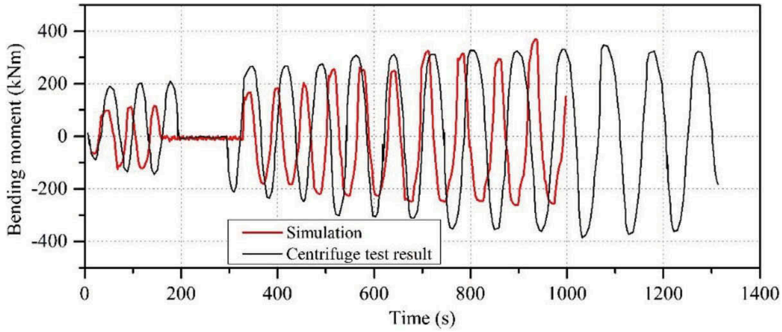

Figure 10. Bending moment in the footing at the center of the base.

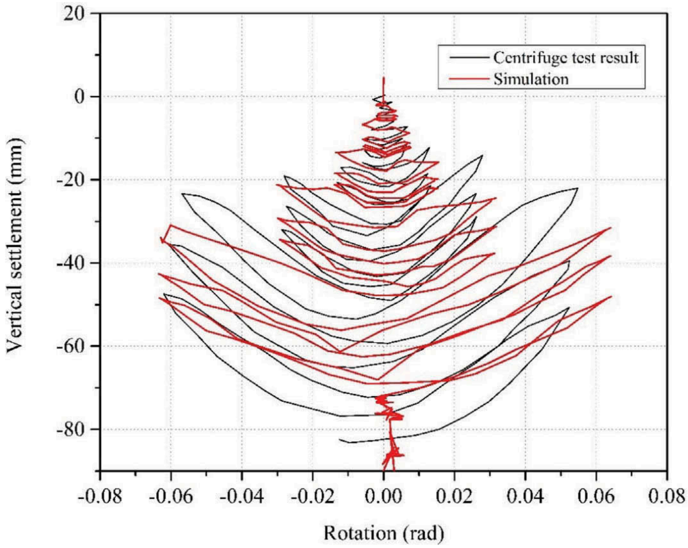

Figure 11. Settlement-rotation behaviour of the footing at the center of the base.

3.2 *Observations and discussion*

It is seen that the OpenSees results are in good agreement with the centrifuge data in terms of capturing the salient features such as maximum moment, shear, rotation and settlement values. In the case of rotational behaviour, error in the prediction of peak rotation of the footing by the BNWF model is less than 10% which is acceptable for practical purposes. Further studies may be attempted with modifications to the BNWF model for better accuracy in the OpenSees simulations. The settlements are predicted reasonably well at lower amplitudes of the cyclic loading. However, at higher amplitudes, the BNWF model overpredicts the settlement of the footing. The sliding behaviour is underpredicted by the BNWF model. This is due to the lack of coupling between the lateral and vertical springs (Gajan et al. 2008). The reduction in shear capacity of the footing due to gapping is not accounted in the BNWF model, which led to the underprediction of the sliding. The maximum moment and shear force developed at the base of the footing is well predicted by the BNWF model. One of the most important design parameters of the foundation design is the permanent deformation at the end of the earthquake event. The settlement-rotation behaviour of the footing confirms the expected mechanism observed at the soil-footing interface. The settlement and uplift of the footing increase as the magnitude of rotation increases. It is seen that the settlement and rotation of the footing match well with the centrifuge results.

4 CONCLUSIONS

The applicability of BNWF model for slow cyclic response analysis of shallow foundation is presented. The BNWF model used the distributed array of nonlinear inelastic springs along with dashpots and gap elements to model the soil-structure interaction. The strip footing finite element model is analysed in OpenSees platform and the results are compared with the slow cyclic centrifuge test results. It is concluded that the BNWF model is capable of predicting the measured responses reasonably well. It is noted that the BNWF model can be used to represent the foundation and underlying soil as realistically as possible to capture the essential features of the SSI. The BNWF model can be adapted to suit any soil and foundation types by modifying the soil stiffness and zero length element springs accordingly. The BNWF model can be used with any suitable design approach for the design of foundations. It is opined that the BNWF model is well suited for the performance-based analysis and design of structures founded on shallow foundations.

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