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TIME DOMAIN NONLINEAR SSI ANALYSIS OF FOUNDATION SLIDING USING FREQUENCY-DEPENDENT FOUNDATION IMPEDANCE DERIVED FROM SASSI

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ABSTRACT

Dynamic soil-structure interaction (SSI) analysis of nuclear power plants is often performed in frequency domain using programs such as SASSI [1]. This enables the analyst to properly a) address the effects of wave radiation in an unbounded soil media, b) incorporate strain-compatible soil shear modulus and damping properties and c) specify input motion in the free field using the de-convolution method and/or spatially variable ground motions. For structures that exhibit nonlinearities such as potential base sliding and/or uplift, the frequency-domain procedure is not applicable as it is limited to linear systems. For such problems, it is necessary to solve the problem in the time domain using the direct integration method in programs such as ADINA [2]. The authors recently introduced a sub-structuring technique called distributed parameter foundation impedance (DPFI) model that allows the structure to be partitioned from the total SSI system and analyzed in the time domain while the foundation soil is modeled using the frequency-domain procedure [3]. This procedure has been validated for linear systems.

In this paper we have expanded the DPFI model to incorporate nonlinearities at the soil/structure interface by introducing nonlinear shear and normal springs arranged in series between the DPFI and structure model. This combination of the linear far-field impedance (DPFI) plus nonlinear near-field soil springs allows the foundation sliding and/or uplift behavior be analyzed in time domain while maintaining the frequency-dependent stiffness and radiation damping nature of the far-field foundation impedance. To check the accuracy of this procedure, a typical NPP foundation mat supported at the surface of a layered soil system and subjected to harmonic forced vibration was first analyzed in the frequency domain using SASSI to calculate the target linear response and derive a linear, far-field DPFI model. The target linear solution was then used to validate two linear time-domain ADINA models: Model 1 consisting of the mat foundation+DPFI derived from the linear SASSI model and Model 2 consisting of the total SSI system (mat foundation plus a soil block). After linear alignment, the nonlinear springs were added to both ADINA models and re-analyzed in time domain. Model 2 provided the target nonlinear solution while Model 1 provided the results using the DPFI+nonlinear springs. By increasing the amplitude of the vibration load, different levels of foundation sliding were simulated. Good agreement between the results of two models in terms of the displacement response of the mat and cyclic force-displacement behavior of the springs validates the accuracy of the procedure presented herein.

INTRODUCTION

A simplified procedure for implementing distributed linear foundation impedance parameters in time domain analyses using ADINA "direct integration method" was previously presented [3]. The method involved: 1) calculating the foundation dynamic impedance at each soil/mat interaction node from soil reaction forces and interaction displacements in frequency domain using SASSI, 2) developing equivalent simple damped oscillators with constant parameters (spring, mass and dashpot) representing the frequency-dependent dynamic impedance, and 3) implementing the results in time domain analyses using ADINA with consistent foundation mass matrix. The accuracy of the above procedure for rigid and flexible mat foundations supported at ground surface was demonstrated by comparing the response of a two lumped mass parameter-foundation analyzed by SASSI and ADINA in frequency and time domain, respectively.

The above procedure was shown to be effective in modeling linear foundation response, which primarily accounts for the far-field foundation stiffness and radiation damping. In addition to the linear far-field response, the foundation soils may undergo significant nonlinear behavior in the near-field of the structure caused by the inertial feedback of the structure into the foundation. Such effects were not included in the procedure described above.

In the following, the above procedure is expanded to include distributed nonlinear springs to account for soil nonlinearity in the near-field of the structure. The accuracy of the new procedure using DPFI model is verified through a test problem.

METHODOLOGY

Let's consider the problem of one-dimensional wave propagation in a semi-infinite soil column with uniform properties (elastic modulus, G, and mass density, ρ), as shown in Fig. 1. The column is subjected to a periodic motion, $U_0(t) = f(-vt)$ at the surface, where v and t are the velocity of this particular wave type and time, respectively. Because the waves travel in one direction only (with no reflections), the displacement response at any point may be written as follows:

$$U(x,t) = f(x - vt) \qquad (1)$$

The particle velocity, U', strain, ε, and stress, σ, at any point along the soil column may be obtained from Equations 2, 3 and 4, respectively.

$$U'(x,t) = df/dt = -v\, f'(x-vt) \qquad (2)$$

$$\varepsilon(x,t) = df/dx = f'(x - vt) \qquad (3)$$

$$\sigma(x,t) = G\, \varepsilon(x,t) = G\, f'(x - vt) \qquad (4)$$

The boundary forces at the surface (x=0) may be then obtained from the stresses in Eq. 4, as shown below:

$$P_0\,(t) = -\,\sigma(0,t)\,.\,A = -\,G\,A\,f'(-vt) \qquad (5)$$

By substituting $v = \sqrt{G/\rho}$ and the particle velocity from Eq. 2 into Eq. 5, we obtain:

$$P_0(t) = (\sqrt{\rho G})\,A\,U'_0(t) \qquad (6)$$

As seen from Eq. 6, the forces at the surface are proportional to the velocity rather than displacement. Therefore, the entire semi-infinite soil column may be replaced by viscous dashpots having $C = \sqrt{\rho G}$ per unit area, as shown in Fig. 1(b). These dashpots represent the effects of linear far-field zone.

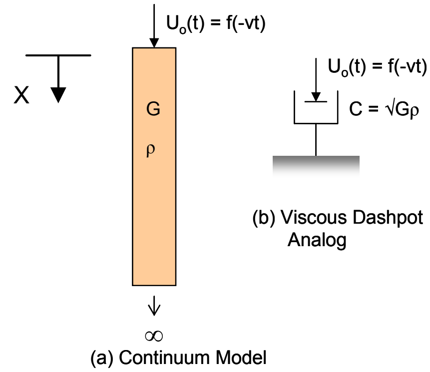

Fig 1 - Simulation of 1-D Wave Propagation in a Semi-Infinite Soil Column

Now let's consider a one-dimensional wave propagation problem with two different material types, as shown in Fig. 2(a). The upper portion consists of a nonlinear material while the lower portion (which continues to great depths) consists of linear elastic material. The solution to this problem can be readily obtained by replacing the entire soil column with a spring and a dashpot in series, as shown in Fig. 2(b). The dashpot represents the lower semi-infinite soil column (far field) while the spring represents the upper nonlinear soil column (near field). In this model the near-field soil mass is ignored. It is noted that the dashpot properties in this case are controlled only by the far-field soil column and are not affected by the properties of the upper soil column, as shown in Fig. 2.

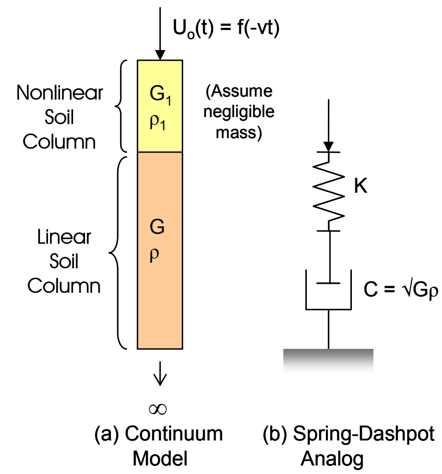

Fig 2 - Simulation of 1-D Wave Propagation in a Semi-Infinite Soil Column with Two Material Types

The above discussion sets the stage for representation of the near-field and far-field foundation impedances in terms of springs and dashpots arranged in series. This representation, as shown in Fig. 2(b), is exact for one-dimensional wave propagation problem. However, in the case of two- and three-dimensional foundation vibration problems, the break up of the near-field and far-field foundation impedances in terms of springs and dashpots is more complex. This is mainly due to the fact that the far-field impedance parameters, in general, are not uniform and are controlled by the foundation configuration and properties as well as soil properties, as opposed to depending on far-field soil column only as in the case of one-dimensional wave propagation. In the following we will present a simplified procedure for developing nonlinear near-field impedance model in conjunction with distributed linear far-field impedance model for use in time domain analysis.

According to the theory of plasticity, the nonlinear foundation deformations may be decomposed into elastic and plastic components, as shown in Eq. 7 (see Fig. 3).

$$U = U^e + U^p \tag{7}$$

Where U is the total displacement; and U^e and U^p are the elastic and plastic displacement components, respectively. Assuming that the plastic deformations only occur in a small zone below the foundation mat, Eq. 7 may be represented by a linear far-field oscillator acting on the elastic component of displacements and a nonlinear near-field spring acting on the plastic component of displacements, as shown in Fig. 4.

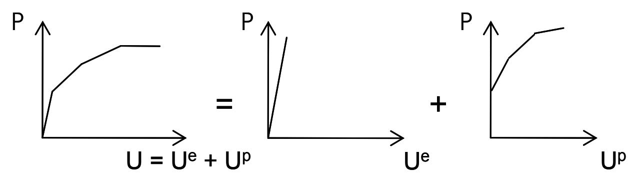

Fig 3 - Decomposition of Near-Field Displacements into Elastic and Plastic Components

When the forces acting on the nonlinear springs are lower than yield forces, P_y, the foundation mat is fully bonded to the soil (i.e. no plastic deformations) and the only deformations are those provided by the linear oscillator representing the far-field impedance. As spring forces exceed the yield forces, plastic deformations start to develop, as provided by the near-field nonlinear spring, and are added on top of the elastic deformations provided by the far-field impedance. At the ultimate load, P_u, the foundation forces distributed to the far-field impedance remain constant while the footing goes through plastic displacements. It is assumed that during plastic deformations, the linear far-field foundation impedances remain constant.

It is also noted that when near-field spring forces are lower than the yield forces, the far-field dashpots representing the foundation radiation damping are fully engaged. When these forces exceed the ultimate forces of the nonlinear springs, the dashpots will be disengaged, as required.

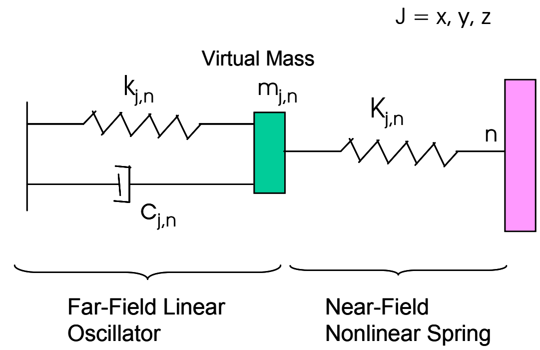

Fig 4 - Near-Field/Far-Field Foundation Model

VALIDATION PROBLEM

Nonlinear foundation vibration response of a two-dimensional strip footing supported at the surface of a uniform half-space and subject to frictional sliding at the base was analyzed in time domain with ADINA using continuum and distributed foundation impedance models. The results were then compared to evaluate the accuracy of the procedure presented above. Both the rigid and flexible footing cases were considered. For the rigid footing case, the footing was modeled with no mass and assigned very stiff properties. For the flexible footing case, the actual footing properties, as listed in Fig. 5 were used. The results of the rigid footing are compared at the center of the footing while for the flexible footing case, the results at both the center and corner of the footing are calculated and compared. Three load cases corresponding to no sliding, moderate sliding and severe sliding of the footing were analyzed by varying the amplitude of the applied force. The no-sliding case represents the linear elastic problem of the far-field foundation vibration response. The elasto-dynamic response of the above system was also analyzed in frequency domain using SASSI. The SASSI results, which are considered accurate, were used as the basis for evaluating the accuracy of the ADINA linear elastic continuum and distributed impedance models (i.e. no sliding of the footing). The results of SASSI analyses were also used to develop DPFI model in terms of constant spring, mass and dashpot parameters, which were used in the ADINA distributed impedance model. The ADINA linear continuum model, having been verified above based on linear elastic analysis was then used to develop the nonlinear foundation response by increasing the amplitude of the applied load beyond the yield force of the sliding elements. The results of the ADINA nonlinear continuum model, which are now considered to be the target solution, were used as basis for verifying the accuracy of the ADINA nonlinear distributed near-field impedance model.

It is noted that the current validation is presented for harmonic forced vibration of a surface-supported mat foundation. Extension of the methodology to transient type input motions and embedded foundations are feasible and will be addressed in future studies.

Model Descriptions

ADINA Continuum Model: Figure 5 shows a two-dimensional plane-strain finite element ADINA model of a strip footing supported on the surface of a uniform half-space. The footing is 28 m wide and is subjected to a horizontal harmonic force of frequency 8 Hz. The structure footing and foundation properties are listed in Fig. 5. To represent the near-field foundation nonlinearity, a series of horizontal frictional elements are attached to the bottom of the footing, as shown in Fig. 6. These sliders are of kinematic hardening type and their force-displacement relationship is shown in Fig. 7. In the vertical direction, the footing is assumed to be fully bonded to the soil (i.e. a very large vertical stiffness, Kz, is used to connect the footing and foundation nodes in the vertical direction, as shown in Fig.6).

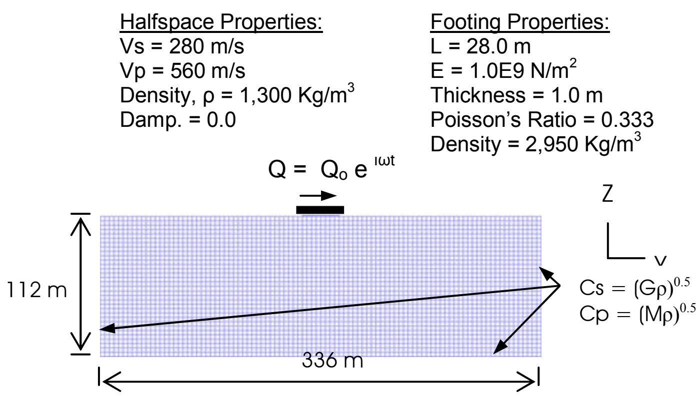

Fig 5 - ADINA Continuum Model of Foundation Vibration

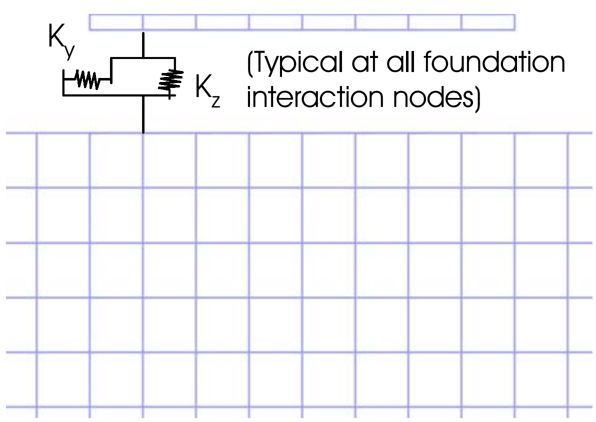

Fig 6 - ADINA Continuum Model Showing Foundation Interface Elements

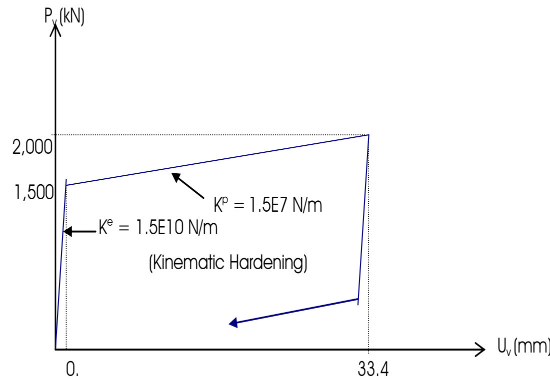

Fig 7 - Constitutive Model of Nonlinear Interface Elements

In order to minimize the reflection of elastic waves arriving at the model boundaries (the so-called "box effect"), viscous dashpots, as described above were attached to the lateral and bottom boundaries of the ADINA model, as shown in Fig. 5. In addition, the lateral and bottom boundaries were placed about 3 and 2 wavelengths away from the footing, respectively, to provide for the effective absorption of the body and surface waves arriving at the model boundaries. The refinement of the finite element mesh was properly selected to satisfy the wavelength criteria for transmitting waves.

SASSI SSI Model: The two-dimensional finite element SASSI model of the strip footing-foundation system is shown in Fig. 8. This model is similar to that of ADINA except that the foundation media is represented by a horizontally layered soil system over uniform half-space. The SASSI analysis is performed in frequency domain and because it properly incorporates energy transmission boundaries, it can accurately calculate the response of structures on semi-infinite half-space. As such, the SASSI results are used as basis to verify the ADINA linear models and to develop the DPFI model.

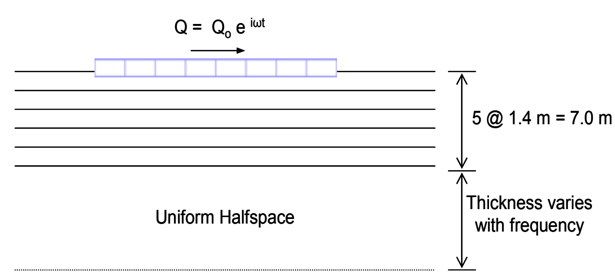

Fig 8 - SASSI Model of Foundation Vibration

ADINA Distributed Impedance Model: The ADINA model of the above strip footing with distributed impedance parameters is shown in Fig. 9. This model was used to verify the accuracy of the procedure presented herein for developing nonlinear distributed foundation impedance parameters. The far-field components of this model consist of horizontal and vertical single degree-of-freedom, damped oscillators with constant parameters, as obtained from SASSI analyses of the linear SSI system. The near-field components consist of nonlinear horizontal springs and very stiff vertical springs arranged in series, as discussed above.

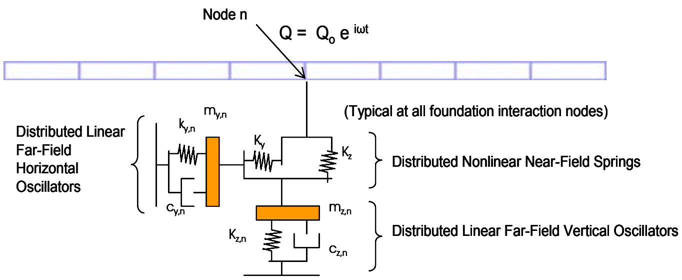

Fig 9 - ADINA Nonlinear Distributed Impedance Model of Foundation Vibration

Comparison and Discussion of Results

The models were analyzed for three load cases, as discussed below:

Load Case 1 – Linear Foundation Response (Q0 = 1,500 kN): In this case the footing is subjected to an 8-Hz harmonic force with amplitude slightly less than 1,500 kN. Because the load amplitude is less than the friction element yield force (Py = 1,500 kN), the footing response is expected to remain in elastic range, i.e. footing fully bonded to the foundation with no sliding at the base. This case constitutes a linear elastic dynamic problem and the ADINA results can be directly compared with those of SASSI using far-field soil model.

Figure 10 compares the horizontal time-history response at the center of the rigid footing, as obtained from SASSI and ADINA continuum and distributed impedance analyses. Figure 11 shows the same comparisons at the center and corner of the footing for the flexible footing case. As seen from Figures 10 and 11, the steady state responses of the footing obtained from ADINA continuum and distributed impedance models are in good agreement with those of SASSI for both rigid and flexible footings. The difference between SASSI and ADINA responses in the early times is attributed to the Fourier Transform procedure and complex frequency response method used in SASSI. This exercise verifies the adequacy of the two ADINA models for capturing the linear far-field foundation response. In particular, it verifies that a) the ADINA foundation continuum model developed above can properly handle the wave transmission for the 8-Hz vibration frequency and b) the ADINA distributed impedance model properly incorporates the linear far-field DPFI model, as obtained from SASSI analyses. The ADINA linear continuum model, as verified above, now becomes the basis for developing the nonlinear foundation vibration response using inelastic near-field friction elements to verify the accuracy of the ADINA nonlinear distributed near-field impedance model.

Load Case 2 – Nonlinear Foundation Response (Q0 = 1,650 kN): In this case the force amplitude is set to Q_0 = 1,650 kN, which is slightly higher than the friction element yield force. The purpose of this case is to let the friction elements slide but not have large displacements that will overshadow the elastic component of the response. This case constitutes a linear far-field problem with moderate near-field foundation nonlinearity. This problem was analyzed with both the ADINA continuum and distributed impedance models. The results in terms of the horizontal displacement time histories and horizontal force versus displacement relationships computed from the two ADINA models for rigid footing case are compared in Figures 13 and 14, respectively. The same comparisons for the flexible footing case are presented in Figures 15 and 16 for computed response at the center of the footing, and Figures 17 and 18 for computed response at the corner of the footing.

The results for the rigid footing case show an excellent agreement between the two ADINA models both in terms of the horizontal displacement time history response (see Fig. 13) and nonlinear force-displacement relationship (see Fig. 14) of the footing. For the flexible footing case, the shape of the steady state displacement time history responses of the footing show excellent agreement with peak amplitudes being within 15 percent both at the center (Fig. 15) and corner (Fig. 17) of the footing for the two ADINA models. The inelastic force-displacement behavior of the footing also shows reasonably good agreement between the two models for the flexible footing case (see Figures 16 and 18).

Load Case 3 – Nonlinear Foundation Response (Q0 = 2,000 kN): In this case the force amplitude is set to Q_0 = 2,000 kN, which is significantly higher than the friction element yield force. This load will cause large inelastic footing displacements that are approximately an order of magnitude greater than the elastic component of displacements. Similar comparison of the results for the ADINA continuum and distributed impedance models are presented in Figures 19 and 20 for the rigid footing case; and Figures 21 and 22 for the footing center of the flexible footing case and Figures 23 and 24 for the footing corner for the flexible footing case.

Again the results for the rigid footing case show an excellent agreement between the two ADINA models both in terms of the computed horizontal displacement time history response and nonlinear force-displacement relationship of the footing. For the flexible footing case, the agreement between the two ADINA models is very much the same as for Load Case 2, as discussed above.

CONCLUSIONS

An effective method for time-domain SSI analysis of foundation sliding using distributed foundation impedance parameters for rigid and flexible mat foundations supported at ground surface was presented. It was shown that when the distributed, near-field nonlinear springs and far-field linear foundation impedance parameters are arranged in series and attached to the bottom of a rigid or flexible mat, it is possible to adequately predict the response of the nonlinear foundation vibration problem in time domain using this simplified analog. Although the method validation was done for a simple case of two-dimensional steady state foundation vibration problem, it is expected to be equally valid for three-dimensional problems subject to transient seismic loading.

It is noted that the use of nonlinear near-field springs in conjunction with linear far-field impedance parameters require developing distributed impedance parameters. This is due to the fact that the distribution of contact stresses below the mat, in general, is highly non-uniform. As such, the accuracy of the methodology presented herein depends on the accuracy of the soil reaction forces and interaction displacements used to develop the distributed foundation impedance parameters. Finally, in this exercise no provision for vertical separation of the footing from the soil was considered (i.e. the footing is assumed to be fully bonded to the soil in the vertical direction). Any such localized de-bonding can significantly affect the frictional resistance of the footing and reduce the amount of foundation radiation damping. Although not verified at this time, the nonlinear distributed impedance methodology presented herein is expected to be able to model the above de-bonding effects.

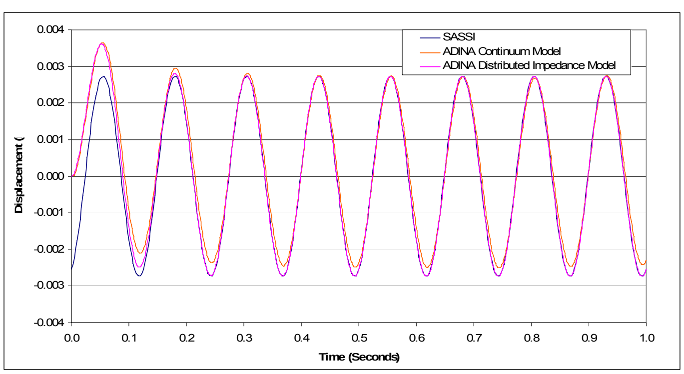

Fig 10 - Comparison of Computed Horizontal Displacements at Footing Center (Rigid Footing, Elastic Response, Q_0=1500 kN)

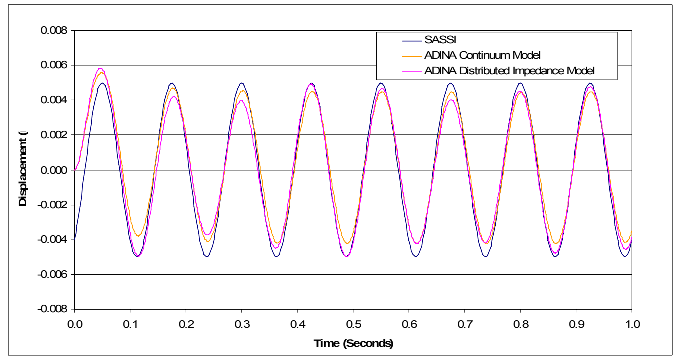

Fig 11 - Comparison of Computed Horizontal Displacements at Footing Center (Flexible Footing, Elastic Response, Q_0=1500 kN)

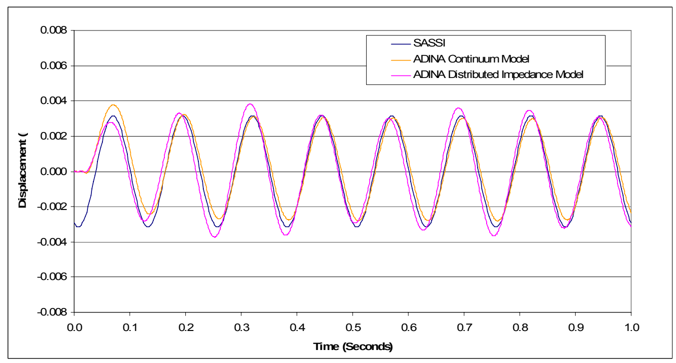

Fig 12 - Comparison of Computed Horizontal Displacements at Footing Corner (Flexible Footing, Elastic Response, Q_0=1500 kN)

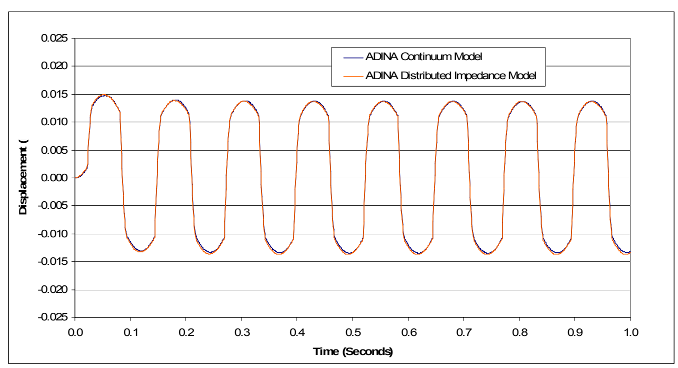

Fig 13 - Comparison of Computed Horizontal Displacements at Footing Center (Rigid Footing, Inelastic Response, Q_0=1650 kN)

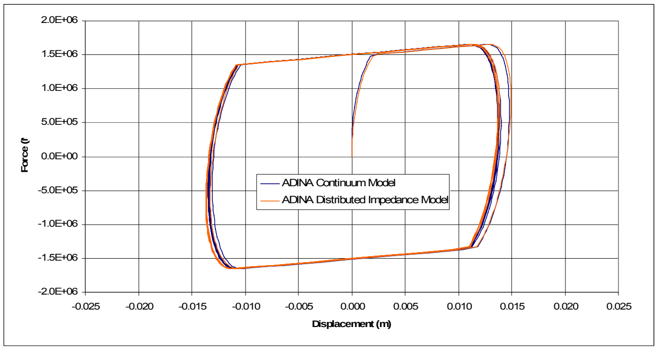

Fig 14 - Comparison of Force versus Displacement Response at Footing Center (Rigid Footing, Inelastic Response, Q_0=1650 kN)

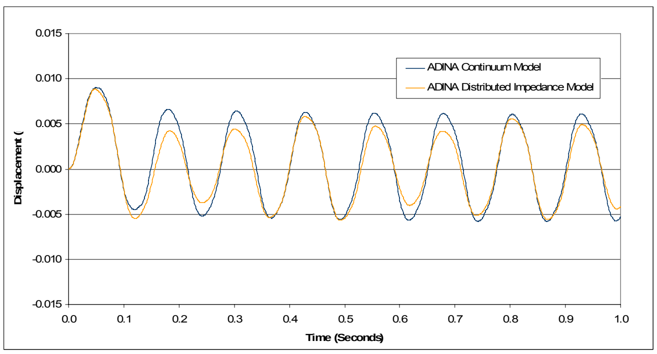

Fig 15 - Comparison of Computed Horizontal Displacements at Footing Center (Flexible Footing, Inelastic Response, Q_0=1650 kN)

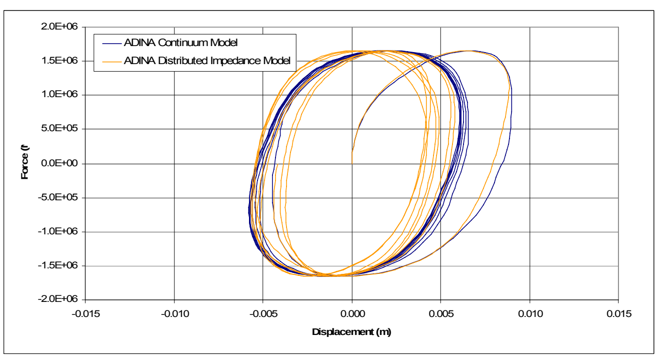

Fig 16 - Comparison of Force versus Displacement Response at Footing Center (Flexible Footing, Inelastic Response, Q_0=1650 kN)

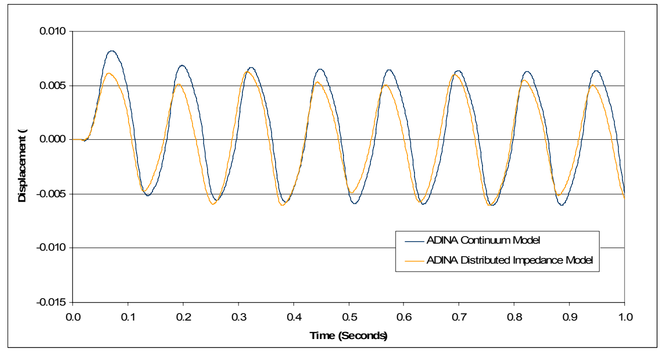

Fig 17 - Comparison of Computed Horizontal Displacements at Footing Corner (Flexible Footing, Inelastic Response, Q_0=1650 kN)

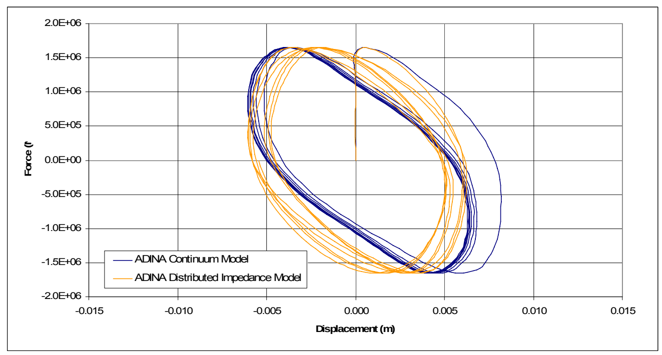

Fig 18 - Comparison of Force versus Displacement Response at Footing Corner (Flexible Footing, Inelastic Response, Q_0=1650 kN)

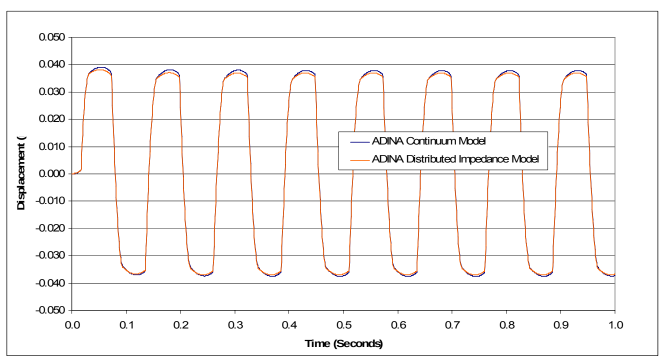

Fig 19 - Comparison of Computed Horizontal Displacements at Footing Center (Rigid Footing, Inelastic Response, Q_0=2000 kN)

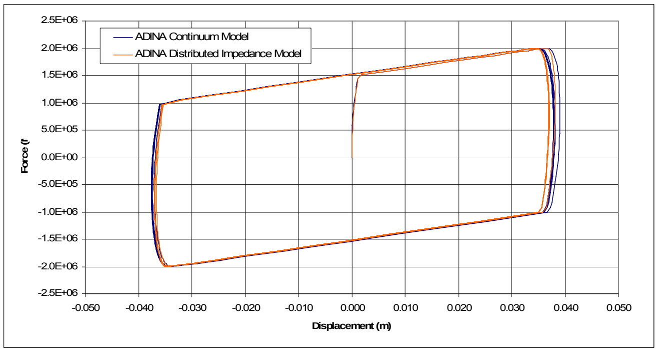

Fig 20 - Comparison of Force versus Displacement Response at Footing Center (Rigid Footing, Inelastic Response, Q0=2000 kN)

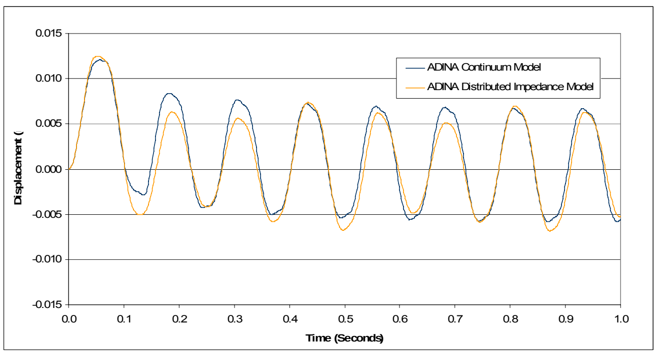

Fig 21 - Comparison of Computed Horizontal Displacements at Footing Center (Flexible Footing, Inelastic Response, Q0=2000 kN)

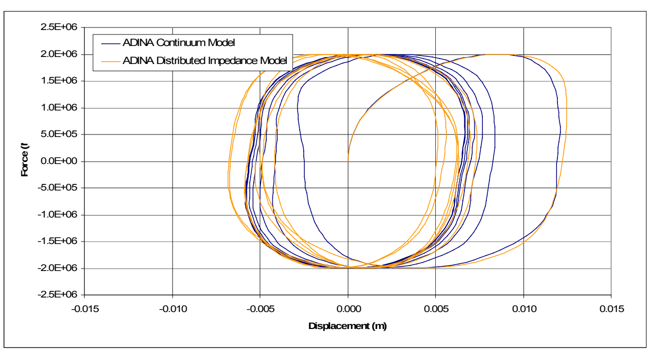

Fig 22 - Comparison of Force versus Displacement Response at Footing Center (Flexible Footing, Inelastic Response, Q_0=2000 kN)

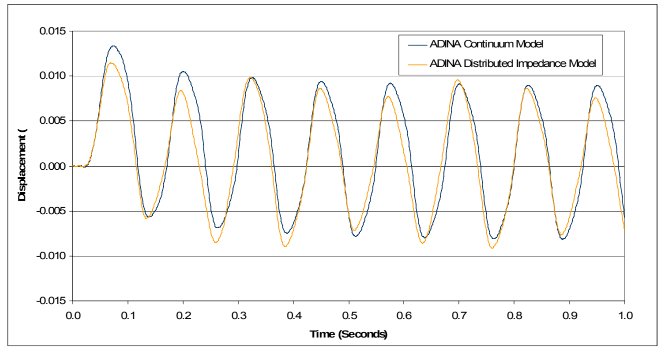

Fig 23 - Comparison of Computed Horizontal Displacements at Footing Corner (Flexible Footing, Inelastic Response, Q0=2000 kN)

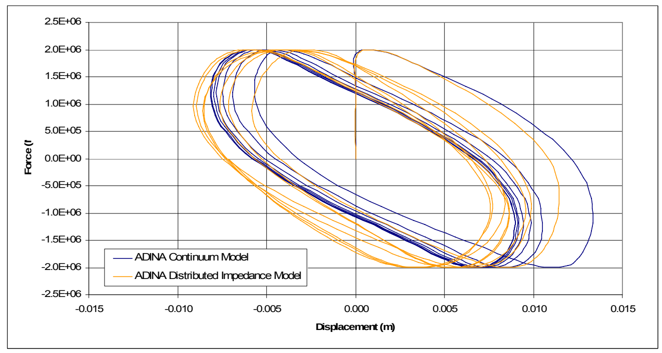

Fig 24 - Comparison of Force versus Displacement Response at Footing Corner (Flexible Footing, Inelastic Response, Q0=2000 kN)

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