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FOUNDATION ANALYSIS OF A LARGE NUCLEAR ISLAND FOR SOIL CASES

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ABSTRACT

This paper describes the foundation analysis of a large nuclear island resting on soft and medium soil sites to obtain forces and moments for basemat foundation design. The Nuclear Island (NI) under study consists of Reactor Building, Containment, four Safeguard Buildings and a Fuel Building resting on a common basemat. The analysis model consists of dynamic (SASSI) finite element model superstructure with the common basemat shell elements replaced by solid elements. The model has soil spring dashpot elements in the three translational directions at the bottom to idealize the soil column behavior and sidewall spring elements that idealize the active, at-rest and passive states of earth pressure caused by the movement of the NI sidewalls against the embedded soil mass. The model represents the sliding interface between the foundation concrete basemat and the underlying soil using 3D contact elements and allows for basemat uplift through compression only vertical springs. The model is loaded with static loads (100% dead loads, 25% live loads, 75% precipitation loads, hydrostatic forces/buoyancy and at-rest soil pressure) before a nonlinear time-history analysis is performed for the soil cases. In-column ground motions at the bottom of the NI common basemat foundation level obtained from SHAKE91 in the three translational directions are used as the input motions to the nonlinear time-history analysis. The dynamic response of the ANSYS model is benchmarked against the results from the SASSI model for validation. The forces and moments obtained from this model are to be used for structural design.

INTRODUCTION

The large Nuclear Island (NI) described in this paper houses a high capacity PWR type reactor. The NI is embedded into the soil with the bottom of the NI Common Basemat embedded approximately 36 ft (Reactor Building) and 41 ft (remaining NI Common Basemat Structures) below plant grade. The Reactor Building (RB) is located in the central portion of the NI Common Basemat Structure and houses the Reactor Coolant System (RCS), which is represented by a 3D lumped mass beam model. The RB consists of two concrete shell structures, which are the inner Reactor Containment Building (RCB) and the outer Reactor Shield Building (RSB). The NI Common Basemat Structure foundation basemat supports both structures. The RCB houses the RB internal structures. The RB is surrounded by Safeguard Buildings (SB) 1, 2, 3, and 4, and the Fuel Building (FB), and four stair towers (included with the SB). The NI Common Basemat Structure foundation basemat supports each of these buildings, which are all safety-related Seismic Category I structures.

The foundation model described in this paper is used only for the basemat foundation analysis and design. For the design of the superstructure, a separate fixed base 3D FEM is used. The forces and moments for the superstructure design are developed by applying the maximum ZPAs from the SSI analysis on a fixed base 3D FEM superstructure model. The forces and moments for the basemat foundation are developed from a time-history analysis in ANSYS (2011) with an NI model developed from the SSI (SASSI) dynamic model. This model is referred as the 3D Basemat FEM.

METHODOLOGY

The 3D basemat FEM analysis consists of the following major steps:

- Two representative soil sites are considered along with their control motions. One soft and one medium soil site are selected for the study (see Figure 1). Their seismic requirements are governed by European Utility Requirements (EUR) soft and medium design ground spectra anchored to 0.3g.
    - The soft site, named 1n2ue, has a 38 ft uniform layer followed by a linear gradient within a 100 ft layer over a half-space. The shear wave velocity, V_s above basemat is 700 ft/s and below basemat is 820ft/s to 1640 ft/s.
    - The medium site named 2sn4ue has 87ft uniform layer over a half-space. The V_s below the basemat varies from 1640 ft/s to 3937 ft/s. The V_s above basemat is 1640 ft/s.

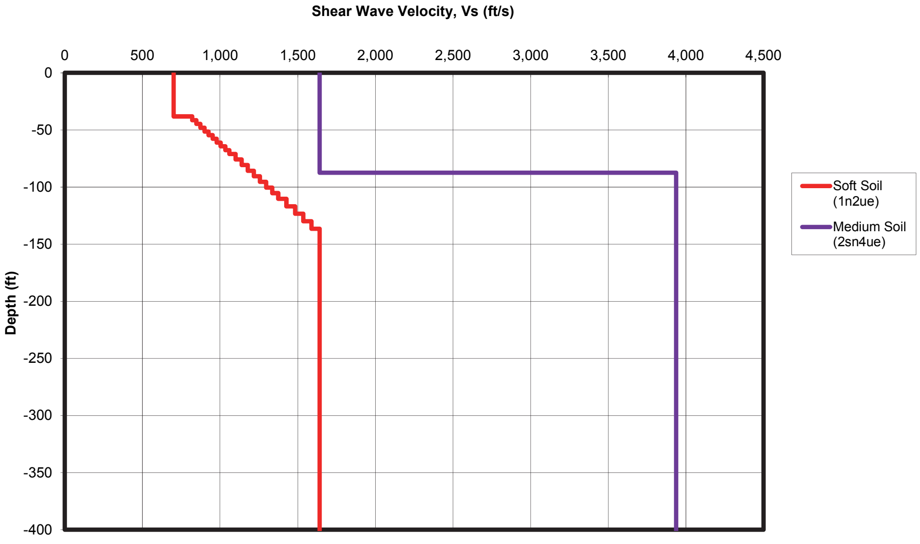


Figure 1. Layered Soft and Medium Soil Profiles.

- An equivalent-linear site response analysis is performed using SHAKE91 to obtain the in-column free-field input motion corresponding to the soft and medium soil profile.
- The basemat foundation structural model (without soil springs) is developed for the NI structures and common basemat based on the SASSI coarse mesh model. A mesh sensitivity study was performed on the SASSI coarse mesh dynamic model to validate its suitability for basemat design forces and moments. Solid elements were selected to model the basemat to account for the shear variation across the thickness of the NI basemat foundation.
- For each of the soil conditions, six DOF frequency-independent bottom soil spring-dashpot values were developed using the embedded Gazetas (1990) method for the idealization of the SSI behavior.

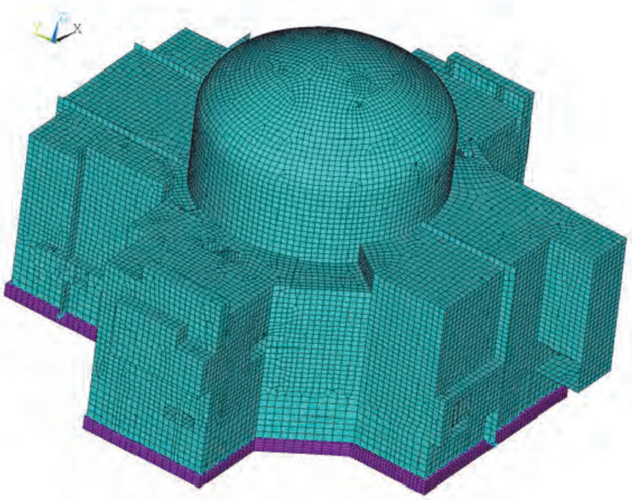
- Sidewall springs were developed considering a geotechnical approach capable of representing lateral earth pressure under seismic loading.
- A time-domain basemat foundation analysis model capable of nonlinear sliding and uplift of the basemat under a transient time-history input is developed by combining the finite element model based on a converted SASSI model, bottom springs and sidewall springs.
- A nonlinear sliding and overturning analysis is performed allowing for basemat uplift and sliding. Dynamic analysis results from ANSYS are compared against SASSI generated results such as driving shear, maximum bearing pressure and maximum uplift area.

MODEL DETAILS AND VALIDATION

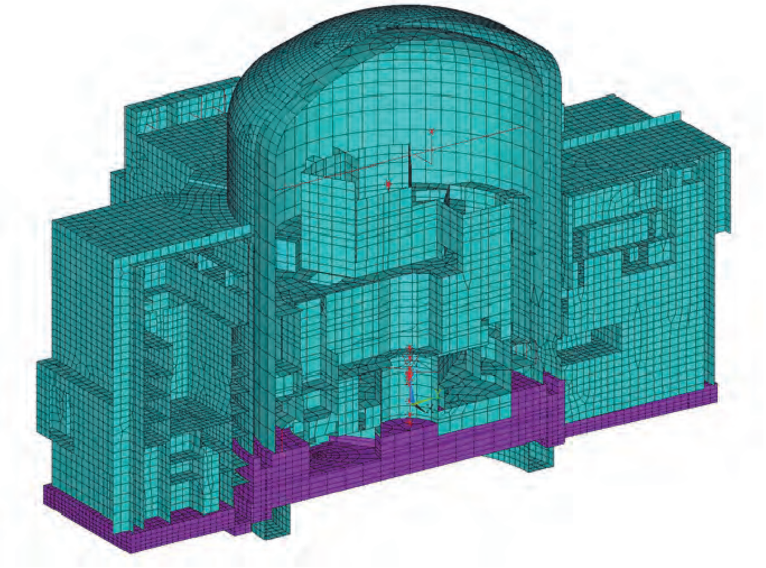
The 3D basemat FEM is used for the analysis and design of the NI common basemat foundation. The FE discretization is selected so that the elements representing elevations and varying thickness of the basemat are able to produce reliable forces and moments for design. The 3D ANSYS basemat FEM consists of solid elements connected to the shell or beam element representation of the superstructure, converted from the SASSI dynamic model. The NI common basemat structure foundation basemat is a cruciform shape that has outline dimensions of approximately 360 feet by 360 feet by 10 feet thick. The basemat foundation consists of solid elements, five layers through the thickness on average. Higher numbers of through the thickness solid layers are used in the foundation mesh below RCB/RB which has a thickness of approximately 12 ft to 16 ft. The particular elements of the ANSYS code used are listed below:

- SOLID45 – An eight-node solid element used to model the common basemat.
- SHELL43 – A four-node shell element used to model walls, slabs and the shell of the RB. This element is suitable for moderately thick shell structures and can also provide out of plane shear forces.
- BEAM4 – Used to model NSSS and Polar Crane.
- BEAM44 – Used to model beams and columns.
- LINK8 and COMBIN39 – A linear 3-D truss element and a non-linear spring element combination used to model sidewall soil springs.
- COMBIN40 – A spring-slider and damper combination element used to model bottom springs.
- MASS21 – Point mass element used to represent structural mass and rotational inertia.
- CONTA178 – 3D node-to-node contact element used to model nonlinear sliding and uplift behavior.

Lumped masses representing the dead and live structural loads are applied to the model in the same manner as applied to the SASSI FEM model. Representations of the FEM are shown in Figure 2.



(a) Model with Superstructure and Solid Element Basemat



(b) Cut View along the YZ Plane

Figure 2. 3D Basemat FEM Model.

The model has soil spring dashpot elements in the three translational directions at the bottom to idealize the soil column behavior and sidewall spring elements for the active, at-rest and passive states of earth pressure caused by the movement of the embedded NI sidewalls against the soil. A parametric comparison of different soil spring formulations was performed for the seismic model. The Gazetas formulation produced displacements and base reactions similar to SASSI and, therefore, was selected and used in the model. Strain compatible shear modulus was used in the calculation of the dynamic stiffness values. The Gazetas equations provide only the dynamic stiffness values and were used in the dynamic analysis. For the static load analysis, one-half of the dynamic stiffness values were used corresponding to the static soil cases. The distribution for seismic and static vertical soil springs is elliptical in nature with stiffer springs on the edges (see Figure 3). Uniform distribution of soil springs is used in the horizontal directions. The Max/Min stiffness ratio for the soft and medium soil cases are 3.22 and 2.72, respectively.

The model represents the sliding interface between the foundation concrete basemat and the underlying soil using sliding elements, and allows for basemat uplift through compression only vertical springs.

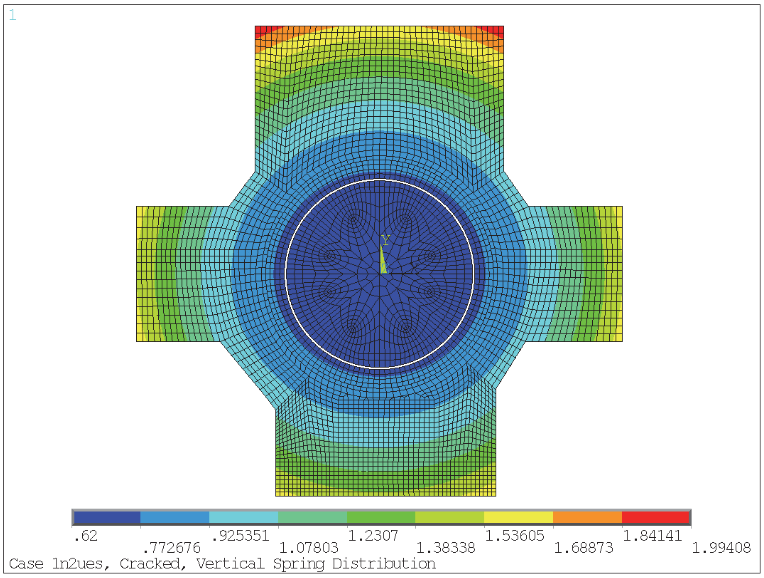


Figure 3. Elliptical Distribution Factors of Soil Springs for Soft Soil Case

The pressure on the buried outer walls that are in contact with soil is a function of the relative movement between the structure and the surrounding soil. The sidewall pressures are idealized by nonlinear sidewall soil springs that represent the following three states: active, passive and at-rest. The guidelines presented in the NAVFAC DM-7.02 (1986) manual were used to compute the sidewall soil springs. In ANSYS, the sidewall springs are modeled using a combination of two elements: a linear 3-D truss element (LINK8) and a non-linear spring element (COMBIN39). The at-rest earth pressure is applied as a preload to the 3-D truss element and the forces developed due to the wall movement (towards and away from the soil mass) are modeled using the nonlinear spring element which is capable of idealizing the different force-deflection curves on the active and passive side. The pressures at a sidewall node are multiplied by the tributary area of the sidewall node to define the sidewall force versus the deflection behavior of a particular sidewall spring.

The 3D basemat FEM is loaded statically by accelerating the lumped and distributed masses before a nonlinear time-history analysis is performed. The initial conditions (dead load, 25% live load, 75% precipitation load, hydrostatic forces and at-rest earth pressures) on the basemat foundation model (nonlinear) are input by performing multiple static analysis load steps prior to the start of the dynamic load. Static load steps are performed in a transient analysis by turning off the transient time integration effects. The static analysis time-steps are performed at solution times less than 0.005sec. The transient itself is started by turning on the time integration effects at time = 0.005sec to the end of the acceleration time-history input. The seismic input motions are in-column ground motions obtained from SHAKE91 analysis runs at the bottom of the NI common basemat foundation level in the three translational directions derived using the NEI approach (see NRC DC/COL-ISG-017 (2010) and NEI white paper (2009)).

The seismic time-history analysis starts from time = 0.005 sec. Thus, effects of the seismic loads are obtained by subtracting the results at time-history data points with the static analysis baseline results. The maximum seismic loads are obtained by determining the maximum/minimum design load values for basemat foundation for each of the elements/nodes over all time points of the transient analysis. In addition to the seismic load, the basemat foundation model is analyzed (with static soil springs) for various static load cases. Based on the results (shears and moments) from the static and dynamic analysis of the basemat foundation model described above, the basemat is designed for the combined effect of the various load cases.

The 3D Basemat FEM was validated against the SASSI seismic analysis to ensure that the two models are dynamically equivalent. The validation was performed by comparing the driving shears, dynamic bearing pressure, and basemat uplift area. Table 1 (a) shows the comparison of the driving shears obtained from the ANSYS and SASSI analyses. Time histories of the total dynamic driving forces acting on the NI structures in the x-, y- and z-directions were calculated by adding all the co-directional dynamic soil spring forces at the bottom and sidewalls (equivalent to the dynamic soil reaction forces at all soil/structure interaction nodes in the SASSI model). In general, the driving shear values in the ANSYS basemat foundation model are higher than the SASSI values. Table 1 (b) shows a comparison of the dynamic bearing pressures generated from ANSYS and SASSI analyses. Finally, a comparison of the uplift area of the basemat, as estimated by ANSYS and SASSI analyses, is shown in Table 1 (c). The uplift area from the SASSI analysis is determined by tracking the nodes that are in tension. If the calculated net total vertical force acting on a basemat node (the sum of the dead load, buoyancy force and z component of the dynamic soil interaction force) is positive, then that node is considered to be in tension (i.e. uplifting). Otherwise, the node is in compression and there is no uplift. In the ANSYS analysis, the total uplift area is calculated by tracking the status of 3D node-to-node contact elements (sticking, sliding or uplifting). The percentage of the total basemat area due to uplift is reported at each time step. The maximum uplift ratio for the duration of the seismic event is reported in Table 1(c). The ANSYS 3D FEM results compare adequately to that of SASSI benchmark results.

Table 1: Comparison of ANSYS 3D FEM and SASSI Model Results.

(a) Driving Shears

Soil Case	ANSYS Basemat Driving Shear Values			SASSI Basemat Driving Shear Values		
	F_X (lbf)	F_Y (lbf)	F_Z (lbf)	F_X (lbf)	F_Y (lbf)	F_Z (lbf)
Soft	2.010E+08	2.119E+08	2.879E+08	1.770E+08	1.872E+08	2.552E+08
Medium	3.986E+08	3.145E+08	3.759E+08	3.385E+08	2.962E+08	3.488E+08

(b) Maximum Dynamic Bearing Pressure

Soil Case	ANSYS Max (Edge) Bearing Pressure (kip/ft^2)	SASSI Max (Edge) Bearing Pressure (kip/ft^2)
Soft	29	30
Medium	34	31

(c) Maximum Uplift Area

Soil Case	ANSYS Uplift Ratio (%)	SASSI Uplift Ratio (%)
Soft	0.0	3.9
Medium	27.2	6.4

RESULTS

Figure 4 shows the salient results for the soft soil case. The minimum factor of safety (FS) against sliding calculated using a base friction coefficient of 0.5 is 1.63. Figure 4(a) shows the demand to capacity ratios for foundation sliding. Total sliding of the foundation does not occur for this analysis case (see Figure 4(b)). However, localized sliding indications are observed in both the X- and Y- directions at a few time-steps. The maximum total sliding area is 32.2%. For the soft soil case, 1n2ue, the basemat does not uplift either locally or globally. The bearing stresses are fully in compression for the basemat for the entire duration of the seismic time-history. The bearing pressures are calculated by normalizing the vertical reaction of the basemat with the corresponding tributary area. In general, the maximum dynamic bearing pressure occurs due to the singularities (stress-concentration) at a corner located at the intersection of two outside edges of the building. Results at the following important time-steps are also presented:

- Maximum X+Y Vector Sum Sliding Displacement Time
- Contact Status at Maximum Basemat Uplift Area Time and
- Unaveraged Dynamic Bearing Pressure at Maximum Dynamic Bearing Pressure Time

Figure 5 shows the salient results for the medium soil case. The minimum factor of safety (FS) against sliding calculated using a base friction coefficient of 0.5 is 1.07. The friction coefficient considered in this study is very conservative. The regulatory stability requirements for sliding factor of safety are demonstrated using separate calculations with SASSI results. Sliding of the foundation does not occur for this case. The stress concentration effect at corner for the dynamic bearing pressure is predominantly noticed for the medium soil case.

SUMMARY AND CONCLUSIONS

A basemat foundation analysis model is developed based on soil spring dashpot values derived using classical methods. Results are presented for a soft and medium layered soil profile housing a large nuclear island foundation. The sidewall springs are based on geotechnical formulations for earth pressure due to the movement of a wall resting against a soil mass. The SASSI model is mainly based on the dynamic (frequency-dependent) properties of the underlying soil deposit derived from mathematical formulations, whereas the ANSYS basemat foundation model is based on classical geotechnical principles which are mostly simplified math formulations validated by test results (e.g., the sidewall springs, distribution of vertical soil springs. etc.,). The ANSYS basemat foundation model and the SASSI model follow different formulations (time-domain versus frequency-domain). The ANSYS basemat model is equipped to capture the design forces and moments through the thickness direction of the basemat foundation by virtue of its multi-layered solid elements representation. The modulus of subgrade reaction in the vertical direction is distributed in an elliptical fashion with softer springs on the center and stiffer springs on the edges to account for the foundation mat rigidity relative to the supporting soil. The results obtained using these two different methodologies show adequate margin of safety against sliding. While the local effects are more pronounced in the ANSYS 3D basemat FEM, the global behavior is similar.

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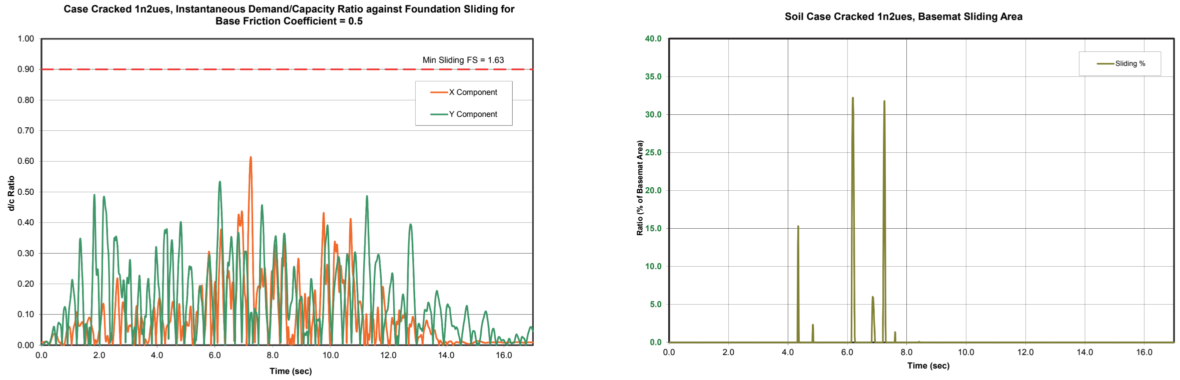
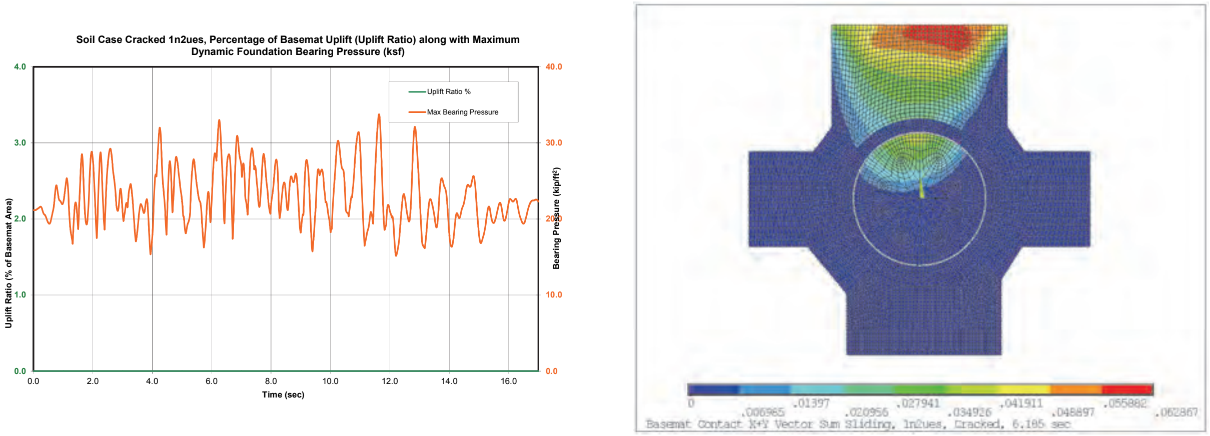


(a) Instantaneous Demand/Capacity Ratio against Foundation Sliding for a Base Friction Coefficient = 0.5

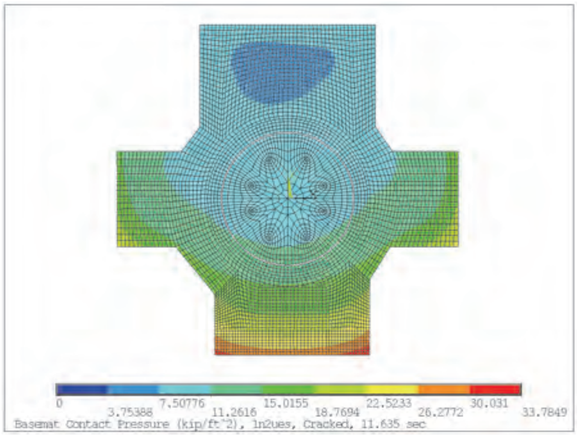
(b) Percentage of Basemat Sliding Area



(c) Maximum Dynamic Foundation Bearing Pressure and Uplift Area

(d) Max X+Y Vector Sum Sliding Movement (in) - Time Snapshot

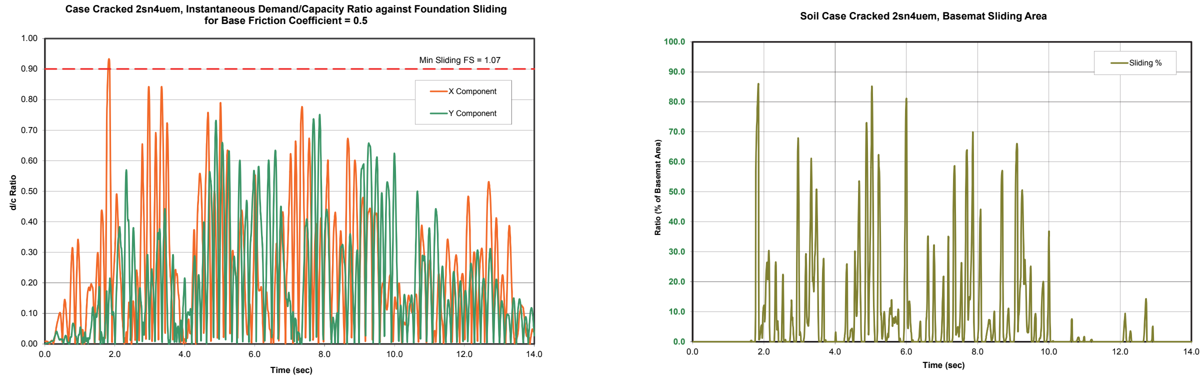
No Uplift was observed for Soft Soil



(e) Contact Status at Max Uplift Area - Time Snapshot

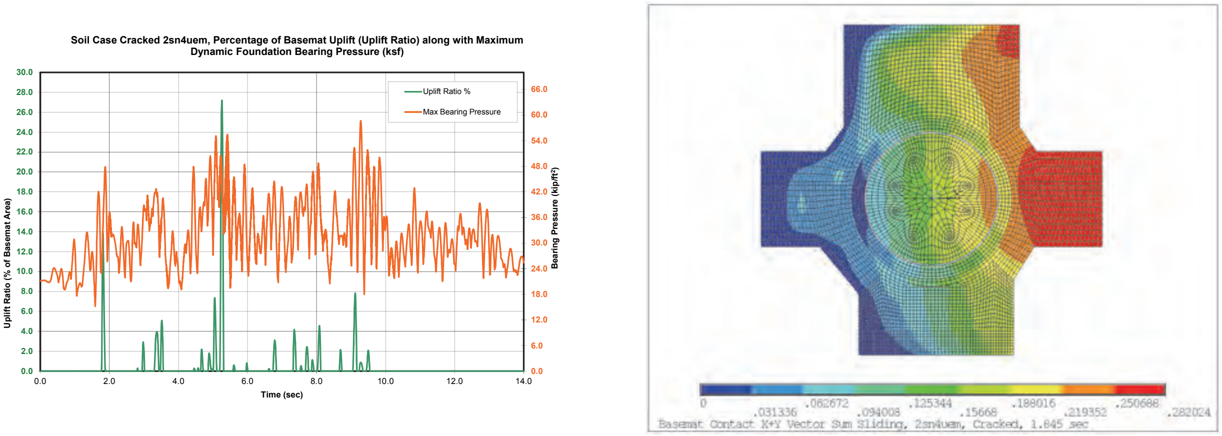
(f) Dynamic Bearing Pressure (ksf) - Time Snapshot

Figure 4. Salient Results for Soft Soil Case



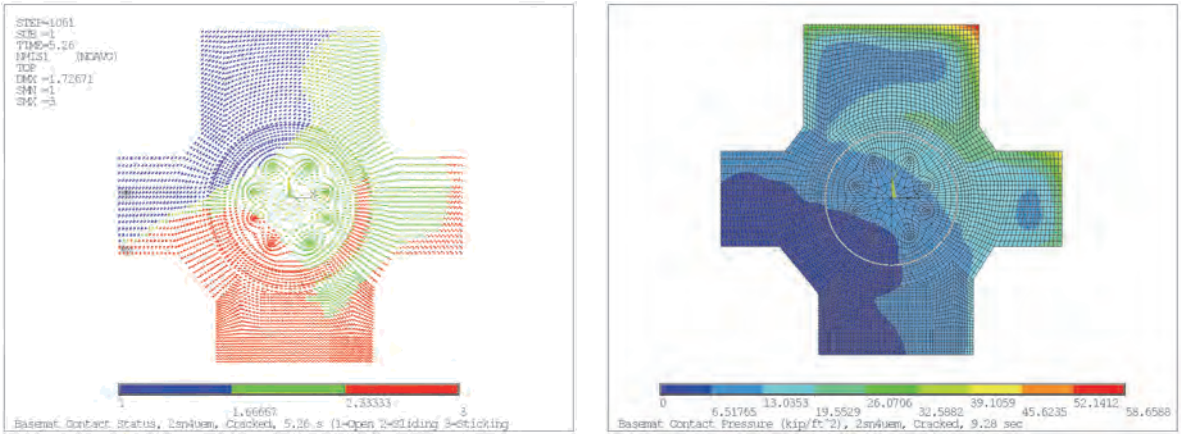
(a) Instantaneous Demand/Capacity Ratio against Foundation Sliding for a Base Friction Coefficient = 0.5

(b) Percentage of Basemat Sliding Area



(c) Maximum Dynamic Foundation Bearing Pressure and Uplift Area

(d) Max X+Y Vector Sum Sliding Movement (in) - Time Snapshot



(e) Contact Status at Max Uplift Area - Time Snapshot

(f) Dynamic Bearing Pressure (ksf) - Time Snapshot

Figure 5. Salient Results for Medium Soil Case