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EVALUATION OF ISFSI PAD FOR SOIL CONSOLIDATION

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ABSTRACT

Independent Spent Fuel Storage Installation (ISFSI) primary structure is the reinforced concrete pad (or basemat) that is used to support the horizontal storage modules (HSM's). The weight of the HSM's containing fully loaded Dry Storage Canisters (DSC's) must be carried by the pad during a design life of 20 years with 40 years life extension utilizing age management and inspection program. Classical calculation of settlement due to consolidation using stress increase estimated by Westergaard or Boussinesq methods, do not account for the stiffness of the pad. This paper describes the process in which the pad is analyzed accounting for both consolidation and the standard Finite Element Analysis (FEA) of slab on elastic foundation. The method utilizes iterations and accounts for the coupling effect of applied load and the settlement of nearby Winkler springs.

INTRODUCTION

Independent Spent Fuel Storage Installation (ISFSI) primary structure is the reinforced concrete pad (or basemat) that is used to support the horizontal storage modules (HSM's) surrounded by an approach slab. The weight of the HSM's containing fully loaded Dry Storage Canisters (DSC's) must be carried by the pad during a design life of 20 years with 40 years life extension utilizing age management and inspection program. If the soil layers underneath the pad consist of sand or rock, settlement will only be an initial settlement immediately after the load is applied.

However, a thick zone of lower strength lean clay and silty clay below the water table will have a limited short-term settlement but will experience appreciable long term settlement due to consolidation of the soil. Water-filled pore spaces take up the initial structure load, however during consolidation, the pressure will start to expel the water from the layer and thus the pore pressure diminishes while the soil particles occupy the space of the evacuated water in a denser configuration. The consolidation manifests itself by settlement at the surface.

Classical calculations of settlement due to consolidation using stress increase estimated by Westergaard or Boussinesq methods do not account for the stiffness of the pad. That is, the pad is assumed flexible. On the other hand, since consolidation is time dependent process, it does not lend itself for 3D finite element modeling of the structural system (pad and soil layers) using available structural software since the consolidation behavior of deep soft soil layer is not easily modeled.

Pan et. al (2017) assumed the Winkler method of uniform modulus of subgrade reaction and using the governing equations of beam on elastic foundation utilizing finite difference method. The

Winkler method idealizes the subgrade boundary condition as a uniform system of independent springs having a linear stiffness related to the coefficient of subgrade reactions. This method does not account for the coupling effect of the springs, i.e., a concentrated load directly above one spring produce settlement at the spring as well as nearby springs. Several methods have been suggested to account for this coupling by varying the coefficient of subgrade reactions underneath the pad. ACI 336.2R provides several approaches including (a) dividing the basemat into central, interior and exterior zone with 3 values of Ks, or (b) doubling the exterior springs. This paper describes the process in which the pad is analyzed including the expected settlement under each region of the pad considering the stiffness of the pad and resulting pressure distribution.

PROJECT DESCRIPTION

The Duane Arnold Energy Center pad 2 was designed to hold up to 34 HSM's housing NUHOMS 61BTH Type 2 Dry Storage Canisters, Figure 1. The proposed basemat is 176' long by 43'4" wide. The HSM's are placed back-to-back in an array of two rows by 17 long, Figure 2. The basemat is 36" thick heavily reinforced concrete. The combined weight of a loaded HSM is approximately 440 Kips and the end shield wall is approximately 89 Kips.

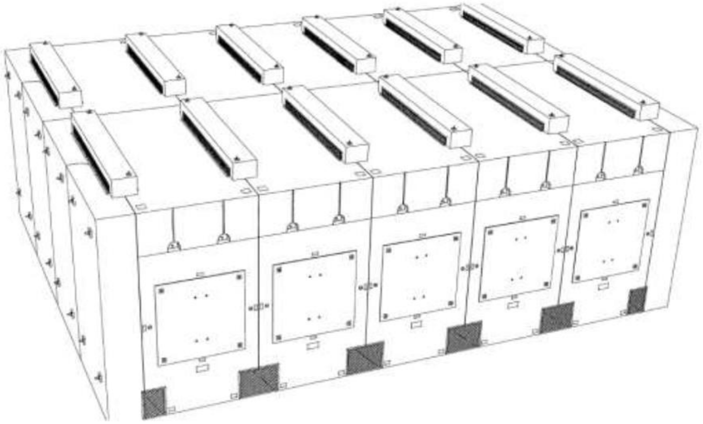


Figure 1. General Arrangement of HSMs

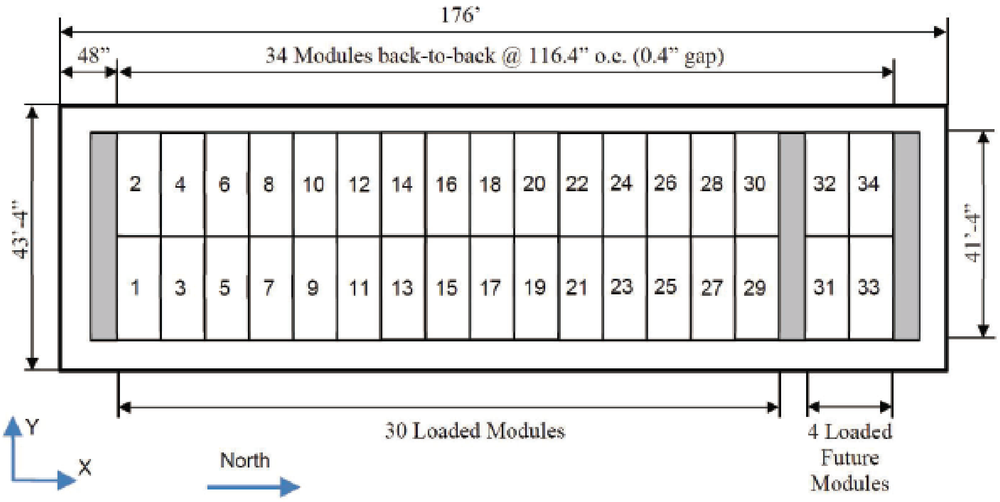


Figure 2. Fully Loaded Pad (34 HSM's) with 3 Shield Walls

The design settlement criteria is the maximum settlement is 6” and the maximum differential settlement is 0.25 in/10ft.

GEOTECHNICAL EVALUATION

Field Exploration

The borings were performed with a Central Mine Equipment truck-mounted (CME-75) rotary drill rig using continuous flight, hollow-stemmed augers and/or a mud rotary procedure to advance the boreholes. Samples were obtained using either thin-walled tube or split-barrel sampling procedures. Upon encountering bedrock and refusal-to-drilling conditions in the boring performed on the southern end of the basemat, the boring was advanced about 10 feet using N size rock core barrel.

Groundwater levels were observed during sampling. A temporary piezometer was installed in the boring performed on the northern end of the basemat, and delayed water level was observed approximately 4 days after completion of drilling.

Based on the results of the soil borings, the general subsurface profile on the site consists of surficial crushed limestone (gravel surfacing) underlain by very soft to medium stiff loess (silty clay and clay) deposits to depths of about 42 to 43½ feet below ground surface. The loess deposits are underlain by glacial fluvial (stiff to hard sandy fat clay and medium dense to dense clayey/silty sands) to depths of about 52½ to 55 feet below ground surface. The glacial fluvial deposits are underlain by stiff to very stiff glacial till (sandy lean clay) to depths of about 90 to 94½ feet below ground surface. Residual sandy silt was encountered below the glacial till in some borings to depths of about 95½ to 96 feet, and is underlain by limestone bedrock. A generalized soil and groundwater profile of the site is shown in Figure 3 below.

The very soft to stiff clay layer that will be subjected to consolidation extends ffrom depths of 4½ ft to 44½ ft below the surface for a total thickness of 40 ft.

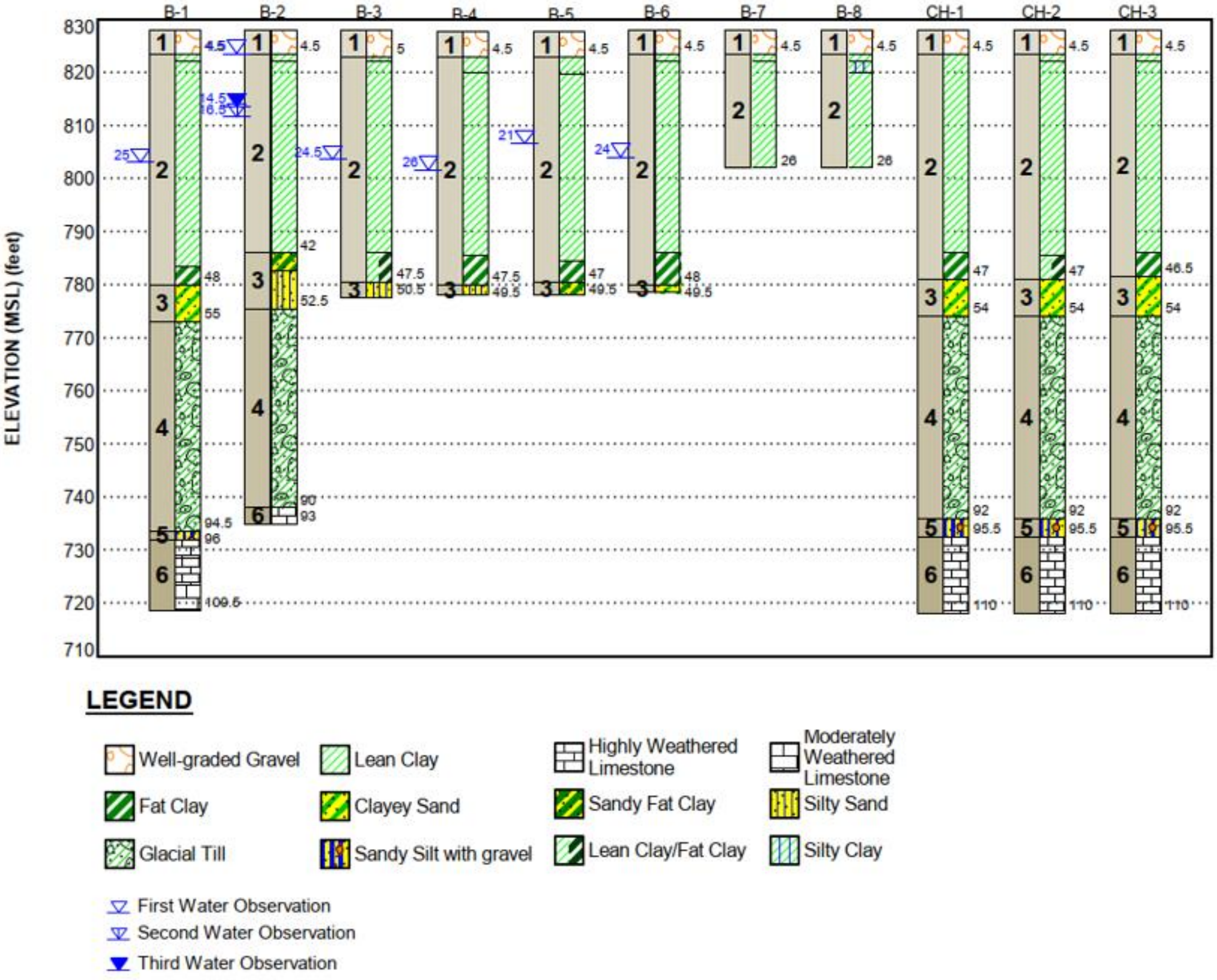


Figure 3. Generalized Soil and Groundwater Profile

Laboratory Testing

Moisture content and index testing was conducted to help characterize and stratify the soil layers, and consolidation testing was conducted on samples of each compressible layer to aid in settlement analysis and estimation of subgrade moduli.

STRUCTURAL EVALUATION

The HSM's which are not attached to the pad (i.e. free standing) are required to function at set limits of total and differential settlements. However, consolidation of a thick layer of soft silt or clay needs to be properly evaluated. The pad on grade is analyzed using finite element (FE) plate/shell elements (for the pad) with linear springs using the coefficient of sub-grade reaction for the soil. This modeling and the FE analysis imply that the soil settlement is only dependent on the spring property and reaction under a specific node and not on the reactions on the nearby nodes. The long term settlement at any point is based on the amount of consolidation which is dependent on the pressure applied on the area as well as the pressure applied on adjacent areas. The pressure as well as settlement on any area of the pad is also dependent on the flexibility (or stiffness) of the pad as it deflects under the load.

A constant coefficient of subgrade reaction (subgrade modulus) will not produce the behavior described above. The pad was analyzed utilizing an iterative method in which an initial value of the coefficient of subgrade reaction is obtained under each subarea of the pad using the pressure distribution from the finite element analysis of the previous iteration. Applying classical geotechnical methodology, the pressure increase at the center of a soil layer is obtained and thus the amount of consolidation in that layer is predicted. The total consolidation for the soil layers in a column is summed up to obtain the settlement underneath the specific area (node). From this settlement and the pressure a new coefficient of subgrade reaction is obtained. The cycle is repeated until the change in the coefficient of subgrade reaction under each area converges.

Geotechnical Analysis

A subsurface model was developed based on the results of the field exploration and laboratory testing. For ease of construction and to distribute the soil pressure load under the basemat, a 3-foot thick layer of cementitious Controlled Low Strength Material (CLSM) was modeled over native soils. A lateral overexcavation of 1H:1V was included in the model around the basemat; these limits of CLSM were included in construction.

Conventional analysis for determining modulus of subgrade reaction considers a uniform pressure is applied to a foundation. The subgrade modulus is calculated based on the pressure applied to the soil and the maximum settlement resulting from the applied pressure. However, on large foundations, the applied pressures and settlement can be non-uniform. The initial settlement calculation assumed uniform pressures acting on the subgrade to estimate the range of settlements and modulus values under perfectly flexible mat foundation. These values were used to estimate an average settlement and modulus values using a simplified model where the mat was divided into three zones of assumed pressure. Subsequent settlement analysis used the results of the finite element analysis (described later) as input of pressure distributions on the basemat to estimate the vertical stress increases in soil below the basemat. The analysis uses uniform pressures acting on discrete zones at ground surface and by utilizing the principles of superposition, the increase in stress at intervals of one foot horizontally and vertically below the basemat is calculated. The vertical stress increases were used to perform consolidation evaluation to obtain settlement distribution throughout the basemat.

In general, individual pressures were provided at discrete points, or nodes, on the basemat foundation based on the finite element model shown in the Figure 4. Based on the pressure distribution from the finite element analysis, the pressures on the basemat were grouped into zones. The increases in vertical stresses at horizontal and vertical distances from any zone were estimated using Boussinesq’s methodology for determining stress below a rectangular area.

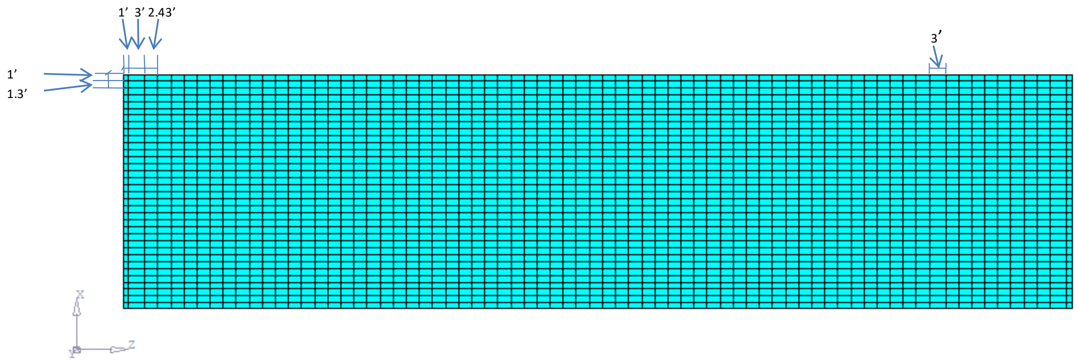
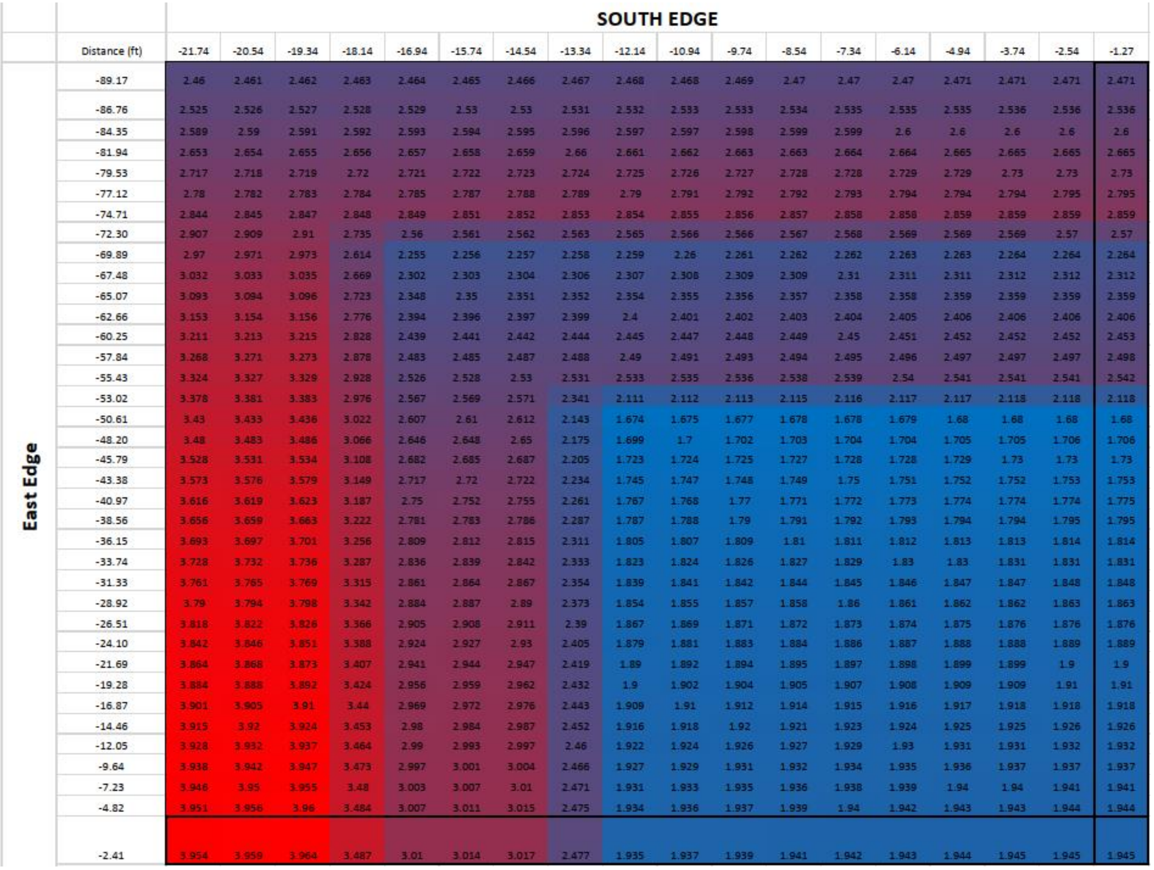


Figure 4. Finite Element model and Node Configuration

An example of the pressure distribution and grouping is provided in Figure 5. For estimating the increase in vertical soil stress and resulting consolidation settlement, these pressures were generally grouped in stress categories to the nearest 500 psf. Cross sections along the short axis (east-west plan direction) and the long axis (north-south plan direction) were analyzed. Due to symmetry for the fully loaded configuration,¼ of the basemat was modeled and the nodes along the center of the mat were analyzed for each axis. For example, the east-west axis was analyzed from the center of the mat with plan view coordinates of (0, 0) to coordinates of (-21.74, 0), and the north-south direction was analyzed from the center of the mat coordinates of (0, 0) to coordinates of (0, -89.17) as illustrated in Figure 5.



		SOUTH EDGE																	
	Distance (ft)	-21.74	-20.54	-19.34	-18.14	-16.94	-15.74	-14.54	-13.34	-12.14	-10.94	-9.74	-8.54	-7.34	-6.14	-4.94	-3.74	-2.54	-1.27
East Edge	-89.17	2.46	2.461	2.462	2.463	2.464	2.465	2.466	2.467	2.468	2.468	2.469	2.47	2.47	2.47	2.471	2.471	2.471	2.471
	-86.76	2.525	2.526	2.527	2.528	2.529	2.53	2.53	2.531	2.532	2.533	2.533	2.534	2.535	2.535	2.535	2.536	2.536	2.536
	-84.35	2.589	2.59	2.591	2.592	2.593	2.594	2.595	2.596	2.597	2.597	2.598	2.599	2.599	2.6	2.6	2.6	2.6	2.6
	-81.94	2.653	2.654	2.655	2.656	2.657	2.658	2.659	2.66	2.661	2.662	2.663	2.663	2.664	2.664	2.665	2.665	2.665	2.665
	-79.53	2.717	2.718	2.719	2.72	2.721	2.722	2.723	2.724	2.725	2.726	2.727	2.728	2.728	2.729	2.729	2.73	2.73	2.73
	-77.12	2.78	2.782	2.783	2.784	2.785	2.787	2.788	2.789	2.79	2.791	2.792	2.792	2.793	2.794	2.794	2.794	2.795	2.795
	-74.71	2.844	2.845	2.847	2.848	2.849	2.851	2.852	2.853	2.854	2.855	2.856	2.857	2.858	2.858	2.859	2.859	2.859	2.859
	-72.30	2.907	2.909	2.91	2.735	2.56	2.561	2.562	2.563	2.565	2.566	2.566	2.567	2.568	2.569	2.569	2.569	2.57	2.57
	-69.89	2.97	2.971	2.973	2.614	2.255	2.256	2.257	2.258	2.259	2.26	2.261	2.262	2.262	2.263	2.263	2.264	2.264	2.264
	-67.48	3.032	3.033	3.035	2.669	2.302	2.303	2.304	2.306	2.307	2.308	2.309	2.309	2.31	2.311	2.311	2.312	2.312	2.312
	-65.07	3.093	3.094	3.096	2.723	2.348	2.35	2.351	2.352	2.354	2.355	2.356	2.357	2.358	2.358	2.359	2.359	2.359	2.359
	-62.66	3.153	3.154	3.156	2.776	2.394	2.396	2.397	2.399	2.4	2.401	2.402	2.403	2.404	2.405	2.406	2.406	2.406	2.406
	-60.25	3.211	3.213	3.215	2.828	2.439	2.441	2.442	2.444	2.445	2.447	2.448	2.449	2.45	2.451	2.452	2.452	2.452	2.453
	-57.84	3.268	3.271	3.273	2.878	2.483	2.485	2.487	2.488	2.49	2.491	2.493	2.494	2.495	2.496	2.497	2.497	2.497	2.498
	-55.43	3.324	3.327	3.329	2.928	2.526	2.528	2.53	2.531	2.533	2.535	2.536	2.538	2.539	2.54	2.541	2.541	2.541	2.542
	-53.02	3.378	3.381	3.383	2.976	2.567	2.569	2.571	2.341	2.111	2.112	2.113	2.115	2.116	2.117	2.117	2.118	2.118	2.118
	-50.61	3.43	3.433	3.436	3.022	2.607	2.61	2.612	2.143	1.674	1.675	1.677	1.678	1.678	1.679	1.68	1.68	1.68	1.68
	-48.20	3.48	3.483	3.486	3.066	2.646	2.648	2.65	2.175	1.699	1.7	1.702	1.703	1.704	1.704	1.705	1.705	1.706	1.706
	-45.79	3.528	3.531	3.534	3.108	2.682	2.685	2.687	2.205	1.723	1.724	1.725	1.727	1.728	1.728	1.729	1.73	1.73	1.73
	-43.38	3.573	3.576	3.579	3.149	2.717	2.72	2.722	2.234	1.745	1.747	1.748	1.749	1.75	1.751	1.752	1.752	1.753	1.753
	-40.97	3.616	3.619	3.623	3.187	2.75	2.752	2.755	2.261	1.767	1.768	1.77	1.771	1.772	1.773	1.774	1.774	1.774	1.775
	-38.56	3.656	3.659	3.663	3.222	2.781	2.783	2.786	2.287	1.787	1.788	1.79	1.791	1.792	1.793	1.794	1.794	1.795	1.795
	-36.15	3.693	3.697	3.701	3.256	2.809	2.812	2.815	2.311	1.805	1.807	1.809	1.81	1.811	1.812	1.813	1.813	1.814	1.814
	-33.74	3.728	3.732	3.736	3.287	2.836	2.839	2.842	2.333	1.823	1.824	1.826	1.827	1.829	1.83	1.83	1.831	1.831	1.831
	-31.33	3.761	3.765	3.769	3.315	2.861	2.864	2.867	2.354	1.839	1.841	1.842	1.844	1.845	1.846	1.847	1.847	1.848	1.848
	-28.92	3.79	3.794	3.798	3.342	2.884	2.887	2.89	2.373	1.854	1.855	1.857	1.858	1.86	1.861	1.862	1.862	1.863	1.863
	-26.51	3.818	3.822	3.826	3.366	2.905	2.908	2.911	2.39	1.867	1.869	1.871	1.872	1.873	1.874	1.875	1.876	1.876	1.876
	-24.10	3.842	3.846	3.851	3.388	2.924	2.927	2.93	2.405	1.879	1.881	1.883	1.884	1.886	1.887	1.888	1.888	1.889	1.889
	-21.69	3.864	3.868	3.873	3.407	2.941	2.944	2.947	2.419	1.89	1.892	1.894	1.895	1.897	1.898	1.899	1.899	1.9	1.9
	-19.28	3.884	3.888	3.892	3.424	2.956	2.959	2.962	2.432	1.9	1.902	1.904	1.905	1.907	1.908	1.909	1.909	1.91	1.91
	-16.87	3.901	3.905	3.91	3.44	2.969	2.972	2.976	2.443	1.909	1.91	1.912	1.914	1.915	1.916	1.917	1.918	1.918	1.918
	-14.46	3.915	3.92	3.924	3.453	2.98	2.984	2.987	2.452	1.916	1.918	1.92	1.921	1.923	1.924	1.925	1.925	1.926	1.926
	-12.05	3.928	3.932	3.937	3.464	2.99	2.993	2.997	2.46	1.922	1.924	1.926	1.927	1.929	1.93	1.931	1.931	1.932	1.932
	-9.64	3.938	3.942	3.947	3.473	2.997	3.001	3.004	2.466	1.927	1.929	1.931	1.932	1.934	1.935	1.936	1.937	1.937	1.937
	-7.23	3.946	3.95	3.955	3.48	3.003	3.007	3.01	2.471	1.931	1.933	1.935	1.936	1.938	1.939	1.94	1.94	1.941	1.941
	-4.82	3.951	3.956	3.96	3.484	3.007	3.011	3.015	2.475	1.934	1.936	1.937	1.939	1.94	1.942	1.943	1.943	1.944	1.944
	-2.41	3.954	3.959	3.964	3.487	3.01	3.014	3.017	2.477	1.935	1.937	1.939	1.941	1.942	1.943	1.944	1.945	1.945	1.945

Figure 5. Pressure distribution from the center of the basemat

The vertical stress increase over these zones were modeled for estimated settlement of the very soft to medium stiff clay layer using the theory of consolidation per the equation below. Based on the results of the field and laboratory testing, this layer was divided into 6 sub-layers.

$$S_c = \frac{C_r H}{1+e_0} log \frac{\sigma'_c}{\sigma'_0} + \frac{C_c H}{1+e_0} log \frac{\sigma'_0 + \Delta\sigma'}{\sigma'_c}, \text{ where}$$

S_c – primary consolidation settlement
C_r – recompression index
C_c – compression index
e_0 – void ratio
H – layer height
σ'_0 – effective overburden pressure
σ'_c – maximum past pressure

$\Delta\sigma'$ – increase in vertical pressure

Based on the estimated settlement and pressure, the coefficient of subgrade reaction (subgrade modulus) k-values (lbs/in^3 or pci) were calculated at each node along the axes analyzed using the following relationship;

$k = q / \delta$, where

q – applied pressure at the node (psi)
δ – estimated settlement under the node (in)

As part of the iteration process, the estimated settlement and corresponding k-values were provided to the structural engineer for incorporation into the basemat structural analysis. The updated pressure distributions were provided to the geotechnical engineer and additional iterations were performed. Two iterations were performed on fully loaded ISFSI mat foundation which consists of 34 HSMs.

FINITE ELEMENT MODEL

The GT-STRUDL (2020) computer code was used to model the basemat (2D 4-node shell elements) on elastic subgrade (Figure 6). Each shell element is approximately 2.43ft x 1.27ft for the area under the HSMs. The element sizes under the shield walls or along the unloaded edges of the basemat correspond to the widths of these locations. To represent the under lying soil, the vertical modulus of subgrade reaction is applied at all elements. GT-STRUDL has the capability of converting the modulus of subgrade reaction (kips/ft^3) to a soil springs stiffness (kip/ft) based on the tributary area associated with each node. An iterative process was utilized with the geotechnical group to achieve the final modulus of subgrade reaction distribution. The GT-STRUDL model was ran with an initial modulus of subgrade reactions. The resulting contact pressure was taken as an output and provided to the geotechnical group in order to develop generalized pressure distributions over discrete areas. The pressure distributions over these areas were modeled for estimated settlement using the theory of consolidation and vertical stress distribution using superposition. Based on the estimated settlement and pressure, new subgrade modulus k-values were calculated at each node along the axes analyzed using (P_{node}/Δ_{node}). Based on these results, the basemat FEM is broken into five groups (K1 to K5, see Figure 7) for the application of modulus of subgrade reactions The iterative process is repeated, GT-STRUDL is run using the new k_s values, contact pressure is found and used by geotechnical group to find new k_s values. Convergence is achieved when there is no appreciable change of the deflection and the subgrade reaction under each region. Only two iterations were performed to reach convergence of a fully loaded basemat foundation.

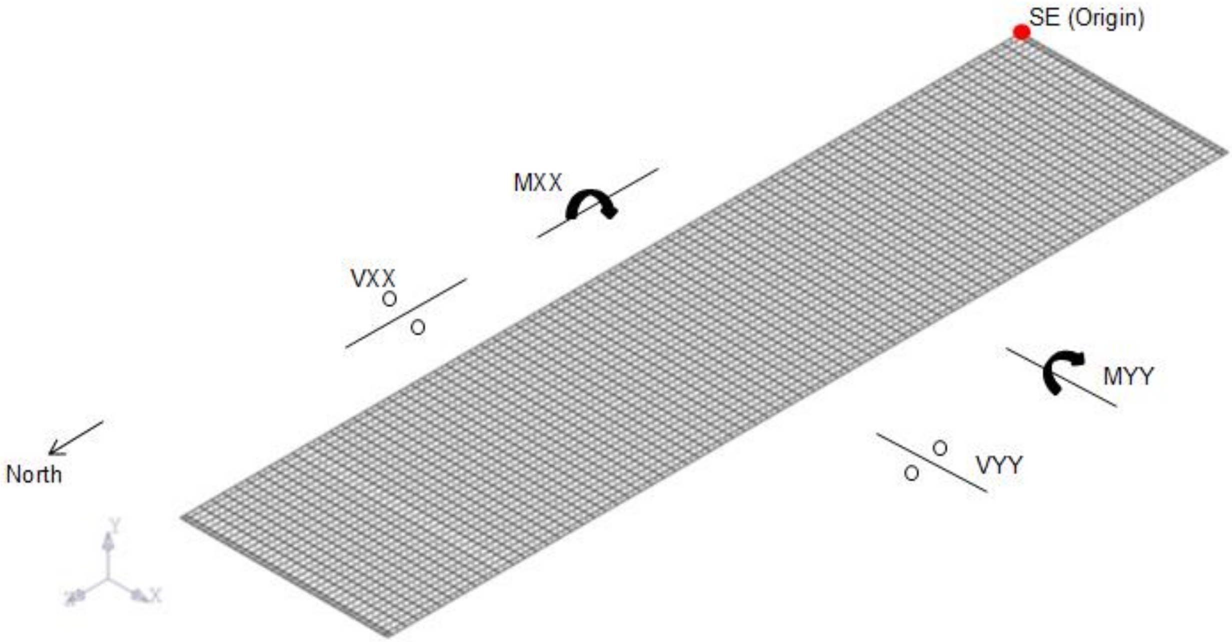
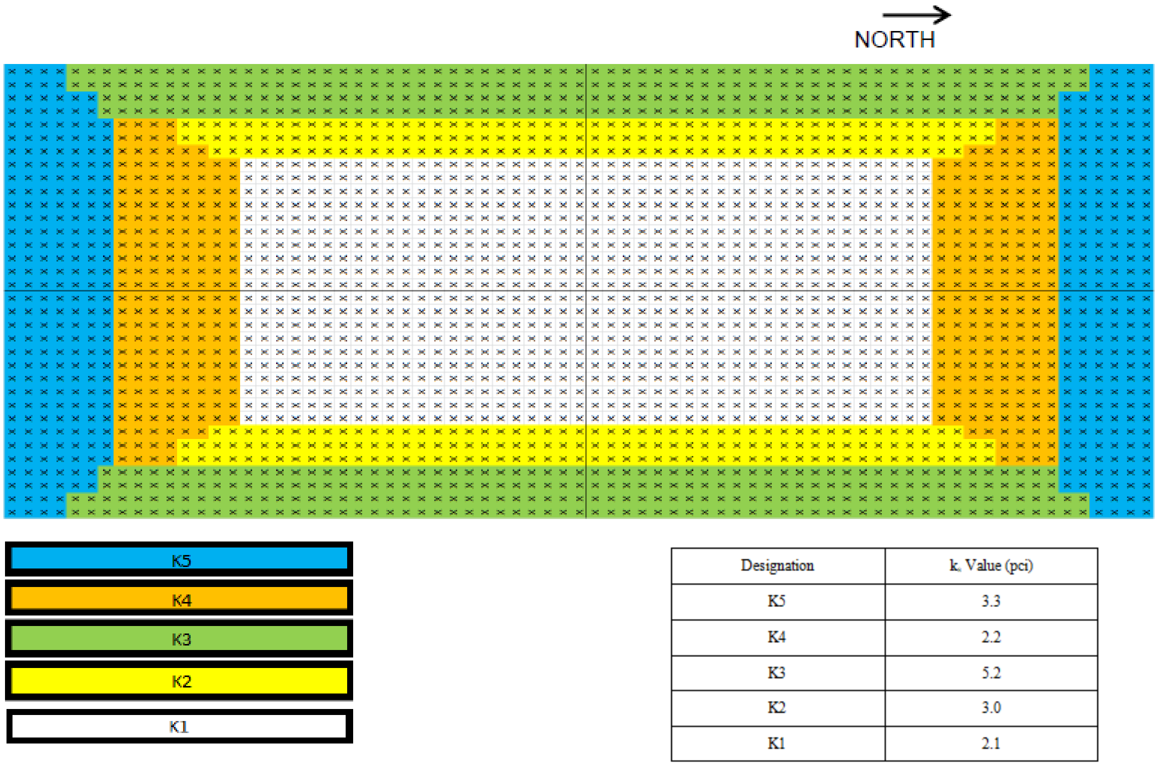


Figure 6. FE MODEL SHOWING DIRECTION OF MOMENT & SHEAR



Designation	k, Value (pci)
K5	3.3
K4	2.2
K3	5.2
K2	3.0
K1	2.1

Figure 7. Modulus of Subgrade Reaction Groups

RESULTS

A plot of the settlement results is shown in Figure 8. The maximum settlement is 5.74in which is accommodated by having the top of the slab elevation of the basemat higher than the approach slab to allow for the uniform settlement. The differential settlement for a fully loaded pad is (5.67in – 5.62in)/(4x2.43ft) = 0.005 in/ft which is less than the required 0.25in/10ft.

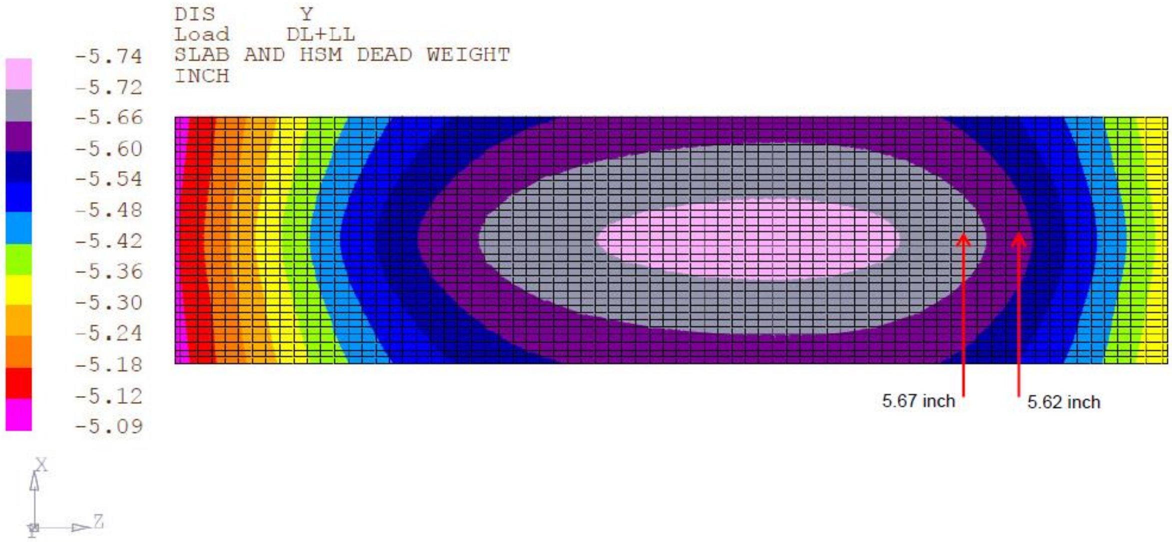


Figure 8. Settlement in inches of Fully Loaded Basemat

CONCLUSION

The iterative method was used to analyze a fully loaded ISFSI pad with deep underlying soft soil layer subjected to consolidation. This method used linear FEA software to account for the pads flexibility/stiffness coupled with consideration of soil consolidation using classical geotechnical methods. The solution converged within two iterations. The results show realistic behavior of slab deformation and subgrade pressure distribution. The fully loaded pad meets the overall and differential settlement requirements.

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