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STATE-OF-THE-ART TECHNIQUES FOR SEISMIC SOIL-STRUCTURE INTERACTION ANALYSIS OF STEEL GRAVITY STRUCTURES

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ABSTRACT

The design of steel jacket fixed offshore structures in zones of moderate seismicity is typically governed by Metocean loads. In contrast the steel gravity structure (SGS) presented in this paper, is a heavy and stiff structure. The large mass results in foundation forces from seismic events that may exceed those created by extreme cyclonic storm events. When computing the earthquake response of such structures it is essential to account for soil-structure interaction (SSI) effects.

Seismic SSI analysis of the SGS platform was performed using state-of-the-art SSI software, which analyzed a detailed three-dimensional model of the SGS supported on layered soil system. The results of this analysis were then compared with those using industry standard impedance methods whereby the layered soil is replaced by equivalent foundation springs (K) and damping (C). Differences in calculated results resulting from the different ways by which K and C are implemented in different software are presented.

The base shear, overturning moment, critical member forces and maximum accelerations were compared for each of the analysis methods. SSI resulted in significant reduction in seismic demands. While it was possible to get reasonable alignment using the different standard industry analysis methods, this was only possible after calibrating the KC foundation model with software that rigorously implements SSI effects. Lessons learned and recommendations for the various methods of analysis are summarized in the paper.

INTRODUCTION

SSI is the process in which the response of the foundation soil influences the response of the structure/foundation and vice-versa. SSI effects can typically be conservatively neglected for lighter non-gravity based offshore structures. However, appropriate inclusion of SSI effects for heavier structures will both allow a more optimized foundation design and also avoid the potential for unconservative design for the foundation, superstructure and equipment/piping systems. The importance of SSI effects in seismic design of concrete gravity structures (CGS) was recognized by previous researchers [1,2,3]. ISO design standards for offshore concrete structures require that SSI be accounted for when performing dynamic analysis [4,5]. CGS projects located in high seismic zones have also considered the use of seismic isolation to further reduce the seismic response of tanks [2] as well as seismic isolation of the topsides as has been implemented in Sakhalin I and II offshore platforms [6].

SSI analysis types fall in two principal categories: direct method and impedance method. In the direct method the structure(s) and the soil are included in one large coupled finite element (FE) model and the dynamic solution is obtained in the time domain thus allowing explicit consideration of soil or structural nonlinearity [7]. The disadvantage of this method is that a very large FE model is required which will mostly consist of soil elements to place the model boundaries sufficiently far from the structure to insure that spurious wave reflection at the boundaries does not affect the response of the structure. As a result the structural part of the model, which is the main reason for the analysis, has to be represented by a simplified model. The impedance model is a substructuring method whereby the SSI problem is solved in three steps, solving kinematics effects by determining the foundation response, the impedance model by establishing the dynamic stiffness of the foundation and the coupled structural/foundation model [8]. In this method the soil nonlinearities can be accounted for using equivalent linear modeling and the dynamic solution can be calculated using the response spectrum method (RSA) or time history method using frequency domain or combination of frequency domain and time domain solutions.

An alternative method for SSI, the Flexible Volume Method (FVM) combines the features of the direct and impedance methods. The SSI problem is analyzed using a sub structuring approach where the problem is subdivided into a series of sub-problems. Each sub-problem is solved separately and the results are combined in the final step of the analysis to provide the complete solution using the principle of superposition. The structure is modeled using finite elements and the impedance is calculated from the dynamic flexibility matrix which is

calculated from dynamic point load solution applied to a layered soil medium. The dynamic solution is obtained using the complex response method in the frequency domain. The methodology is implemented in SASSI program [9] which is the preferred choice for performing SSI analysis of complex structures on arbitrary shaped flexible foundations including embedment effects. Recently the SASSI program has been modified incorporating advances in computer processing technologies. The new program, MTR/SASSI [10], makes it possible to efficiently analyze structures with over 100,000 nodes [11] thus eliminating the need for simplifying the structural model.

The objective of this paper is to compare the MTR/SASSI results with the results of various computer programs that use the impedance method to represent the foundation soil media and provide calibration for the various methods that use solutions that are less rigorous than MTR/SASSI. Both the modal superposition RSA procedure commonly used for the ELE analysis and THA used for the ALE analysis were considered. To that effect the results from four widely used computer programs, which implement foundation stiffness and damping using different procedures, were compared. For the RSA -- SACS and CAPFOS using constant modal damping that can also vary for each mode, ANSYS using composite modal damping, and SAP2000 using viscous dashpots. For the THA – CAPFOS and ANSYS use equivalent Rayleigh damping and viscous dashpots SAP2000 uses viscous dashpots. All software use modal analysis for the RSA with the exception of SAP2000 which can also use Ritz vectors. The THA analysis is performed in the frequency domain in SASSI and time domain in ANSYS, CAPFOS (direct integration) and SAP2000 (Modal or Ritz superposition). The results are then compared with those of SASSI that explicitly models the soil media as semi-infinite layered soil system.

NOMECLATURE

ALE	Abnormal Level Earthquake
C	Foundation Damping
CGS	Concrete Gravity Structure
DOF	Degrees-of-freedom
ELE	Extreme Level Earthquake
FE	Finite Element Model
FNA	Fast Nonlinear Analysis
FVM	Flexible Volume Method
G	Shear Modulus
G^*	Complex Shear Modulus
K	Foundation Stiffness
KMC	Dynamic impedance spring, mass and dashpot
LB	Lower Bound
LRLS	LB rock blanket over LB soil
LRUS	LB rock blanket over UB soil
M	Foundation Fictitious Mass
PSHA	Probabilistic Seismic Hazard Assessment
RSA	Response Spectrum Analysis
SASSI	System for Analysis of Soil-Structure Interaction
SGS	Steel Gravity Structure
SSI	Soil-Structure Interaction
T	Period (sec.)
THA	Time History Analysis
UB	Upper Bound
URLS	UB rock blanket over LB soil
URUS	UB rock blanket over UB soil
V_s	Shear Wave Velocity (m/s)
V_p	Primary Wave Velocity (m/s)
β	Material Damping Ratio (%)
ν	Poisson's Ratio

STRUCTURE DESCRIPTION

The SGS platform consists of a single integrated topside facility of approximately 35,000 tons, and a steel gravity substructure weighing approximately 22,000 tons installed in 70m water depth. The platform is constructed offshore, and floated to its final position where it is installed and ballasted in on a gravel pad 0.5 to 1 m thick. The SGS base footprint is about 75 by 103 meters, with four square foundations (22.5 x 22.5 meters) resting on the gravel pad overlying the insitu ground, which is relatively stiff rock. The foundation mats are connected by four horizontal pontoons. Only the four foundation mats contact the seabed, with each foundation located centrally beneath each of the corner columns. The four SGS columns are 14m square with rounded corners near the waterline and increase to 24m square at the foundation level. The columns and pontoons form the main structural elements of the sub-structure. These are welded rectangular tube type assemblies with internal longitudinal and transverse stiffeners. The columns have orthogonal vertical bulkhead stiffeners running through their entire height providing additional stiffness to the outside tube assembly. Near the mid-height of the columns are tubular truss cross bracings inter-connecting the columns and the pontoons. Cylindrical stubs (3.8m diameter) at the top of each column provides support for the topsides and interface for the topsides installation. The topside is constructed of steel beams forming truss sub-assemblies combined to form the structural system. The flare boom is a major steel truss sub-structure attached to the topsides. Steel floor decks act as diaphragms providing in-plane horizontal stiffness. Various production equipment and the living quarters module are installed on the topside at various locations and are represented by their respective masses. To achieve adequate foundation stability, approximately 120,000 MT of solid ballast will be used to prevent foundation movement during seismic and cyclonic storm events. When computing the dynamic response of such structures to earthquakes and waves it is essential to account for soil-structure interaction (SSI) effects.

SEISMIC DESIGN GROUND MOTION RECORDS

A probabilistic seismic hazard assessment (PSHA) was performed for the platform site. The platform was analyzed for two design level earthquakes, the ELE (Extreme Level Earthquake) with a return period of 500 years; and the ALE (Abnormal Level Earthquake) with a return period of 3000 years. The design spectra were developed at the ground surface for site class C conditions and are shown in Figure 1. The vertical design spectra were assumed to be half the horizontal spectra. Seven sets of acceleration time histories were selected and spectrally matched to the 5 percent damped ELE design spectra, and a different set of seven time histories were spectrally matched to the 5 percent damped ALE design spectra. In the analysis input time histories were specified at the mudline. While seismic ground accelerations at the site are low to moderate, the large SGS mass will result with foundation design forces that equal or perhaps exceed those created by cyclonic storm events thus necessitating a detailed seismic analysis.

DYNAMIC SOIL PROPERTIES

The SGS is supported on a rock blanket which is assumed to be 1m thick on an idealized soil profile representative of Site Class C. The soil is assumed to be 50m thick with constant properties overlying an elastic halfspace. The analyses were performed for four foundation sediment cases for both lower bound (LB) and upper bound (UB) conditions. These four foundation cases included:

- LB rock blanket over LB soil (LRLS)
- LB rock blanket over UB soil (LRUS)
- UB rock blanket over LB soil (URLS)
- UB rock blanket over UB soil (URUS)

The foundation cases also corresponded to two earthquake strain levels (ELE and ALE), making a total of eight analysis cases. The assumed foundation material properties for all cases are summarized in Table 1. These are assumed to be strain compatible and no additional adjustment is made to the soil modulus. The semi-infinite halfspace properties were: V_s = 953 m/s, Poisson's Ratio = 0.30 and damping = 3%.

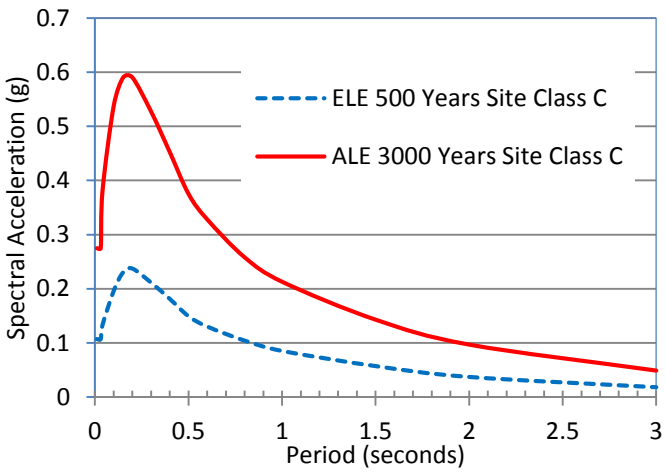

Figure 1. Horizontal Earthquake Design Spectra (5% Damping) for ELE and ALE

Table 1. Idealized Dynamic Site Properties

Material Type	Material Properties	ELE		ALE	
		LB	UB	LB	UB
Rock	V_S (m/s)	178	289	110	222
	ν	0.25	0.25	0.25	0.25
	β	10%	8%	17%	12%
Soil	V_S (m/s)	250	573	177	491
	ν	0.495	0.495	0.495	0.495
	β	6%	3%	14%	4%

MODEL DEVELOPMENT AND VALIDATION

The design team had developed a design level ANSYS [12] three-dimensional model of the structure for static analysis, see Figure 2. The SGS was modeled with 3D shell elements and the topsides with beam elements and consisted of 261,000 elements and 157,000 nodes. A dynamic model was then developed by incorporating added and entrapped mass and ballast. The updated ANSYS dynamic model was converted to MTR/SASSI without major alteration to the element and node numbering scheme used in ANSYS.

The various checks that follow were performed to verify the conversion:

- Compare the total weight and center of gravity for the topsides, SGS, entrapped and hydrodynamic mass.
- Check the static stiffness of the models by applying unit forces at the top of the legs and comparing displacements.
- Check the dynamic stiffness of the two models by applying uniform static accelerations equivalent to 1g applied in the x, y and z directions and compare displacements. In addition the base shear and base overturning between the two models were compared. For example with 1g load in the y direction the ANSYS base shear was 3,258 MN and SASSI was 3,259 MN and the overturning moments were 110,503 MN-m and 110,593 MN-m.
- Compare fixed-base natural frequencies from ANSYS with MTR/SASSI. The first two natural periods from ANSYS were 2.7 sec. and 2.72 sec. in the x and y directions and from SASSI 2.73 sec. for both x and y.

Based on these comparisons it was concluded that the ANSYS dynamic model was accurately converted to MTR/SASSI.

For the SSI analysis the detailed model, Figure 2, was simplified. Although it would have been possible to use the detailed model to perform the SASSI SSI analysis it was necessary to simplify the detailed SGS/Topsides model to make it more amenable to the various analysis techniques that were used in the comparisons presented below. The simplification involved converting the SGS legs, pontoons and bracing from plate elements to equivalent beam elements (stick model), see Figure 3. The topsides model was kept as it was in the detailed model. Fixed base time history analysis (soil is assumed to be rigid) was performed using SASSI. The results obtained from the fixed base simplified model compared favorably with the response obtained from the detailed fixed base model.

SASSI SSI Analysis

The simplified SASSI SGS model was then supported on a layered soil medium with the properties defined in Table 1. Time history analysis was performed in the frequency domain to calculate the SSI response. The SASSI SSI results form the basis of the analyses and are used to verify and align the results obtained using the other different analysis methods described in this paper. To demonstrate the effects of SSI on the dynamic response of the SGS the average fixed base response spectra calculated at the base of the SGS (dashed lines) are compared with the response spectra with SSI included (solid lines) in Figure 4. The spectra in the x, y and z directions are shown. It can be seen that in both the horizontal and vertical direction there is a significant reduction in response below 0.25 seconds. The maximum zero period accelerations are also reduced. Figure 4 also shows that response at longer periods can be amplified if SSI is included. This could be mainly due to rocking of the structure. This reduction in response is even more strongly manifested when comparing the average response at the top (EL +23.1m above MWL) of the SGS columns, see Figure 5.

The foundation reaction forces calculated using MTR/SASSI for fixed base conditions, LRLS and URUS are compared in Table 2. They represent the average for nine input time histories for the ALE. The beneficial effects of SSI can clearly be seen. As the foundation strata become more flexible the loads are reduced. For example the base shear for the softest soil case analyzed, LRLS, is reduced by 52 percent.

Table 2. Comparison of MTR/SASSI Foundation Loads for ALE

	Fixed Base	URUS	LRLS
Max. Base Shear (kN)	633,056	515,889	298,429
Max. Overturning Moment (kN-m)	14,738,666	13,468,995	8,222,983
Maximum Base Normal Force (kN)	904,994	873,650	555,369

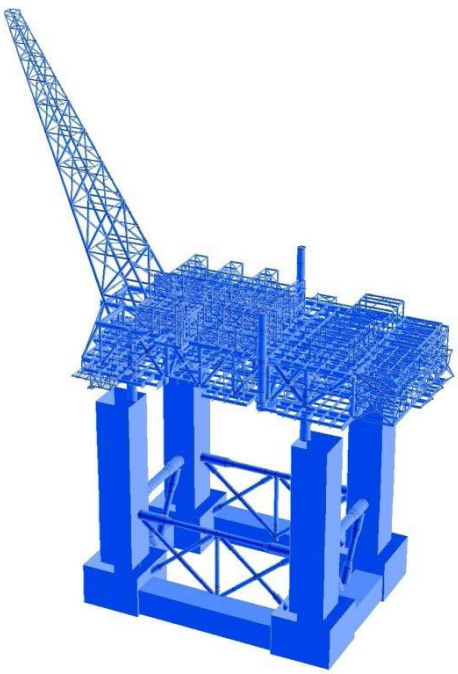

Figure 2. Detailed SGS and Topsides Model

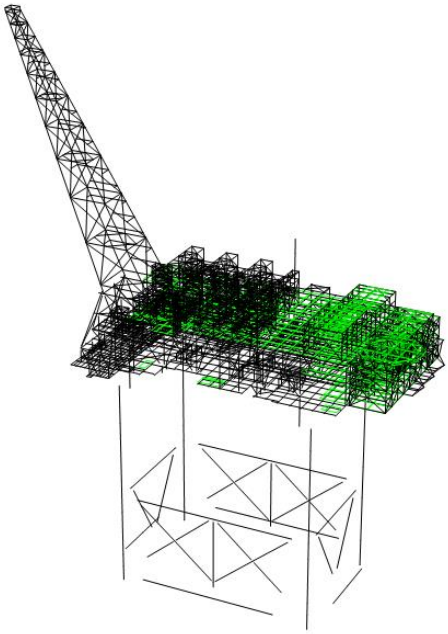

Figure 3. Simplified SGS and Topsides Stick Model

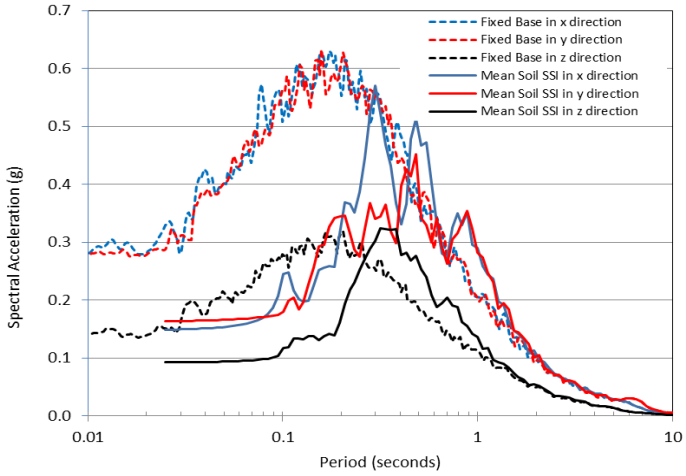

Figure 4. Comparison of Fixed Base and SSI Response Spectra at Base of SGS, ALE

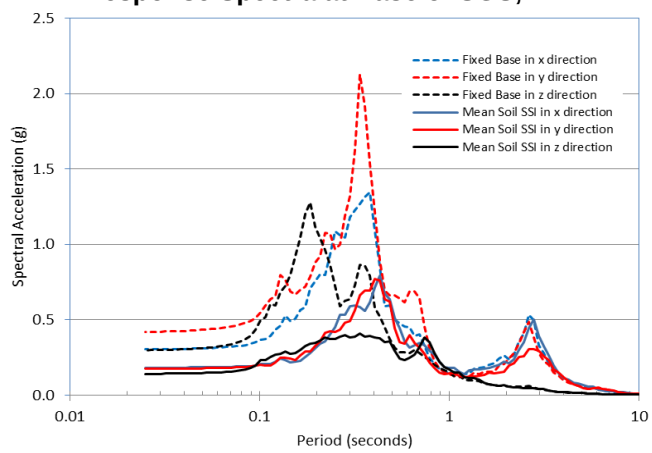

Figure 5. Comparison of Fixed Base and SSI Response Spectra at Top of SGS Columns, ALE

Foundation flexibility

In most SSI analyses, especially for foundations that are founded on the surface of a soil medium, the substructure problem is simplified by assuming that the foundations are structurally rigid. This allows reduction of the SSI problem to a set of springs and dashpots that are then attached directly to the structural model. This is usually referred to as the impedance method. SASSI has the ability to perform such analysis in addition to the more detailed SSI approach described in the previous section using the flexible volume method. In order to test the effect of foundation flexibility on the overall response one of the SASSI cases was repeated after modifying the foundation footings to behave as rigid structures. The spectra at the top of one of the columns are compared in the x, y, and z directions and are shown in Figure 6. It can be concluded that for the foundation cases analyzed, the foundation flexibility does not significantly affect the SSI response. This conclusion is strongly dependent on the foundation rigidity and cannot be generalized to other structures without performing a similar type analysis with SSI software such as SASSI that can account for foundation flexibility. The remaining analysis methods investigated in this paper all assume a structurally rigid foundation.

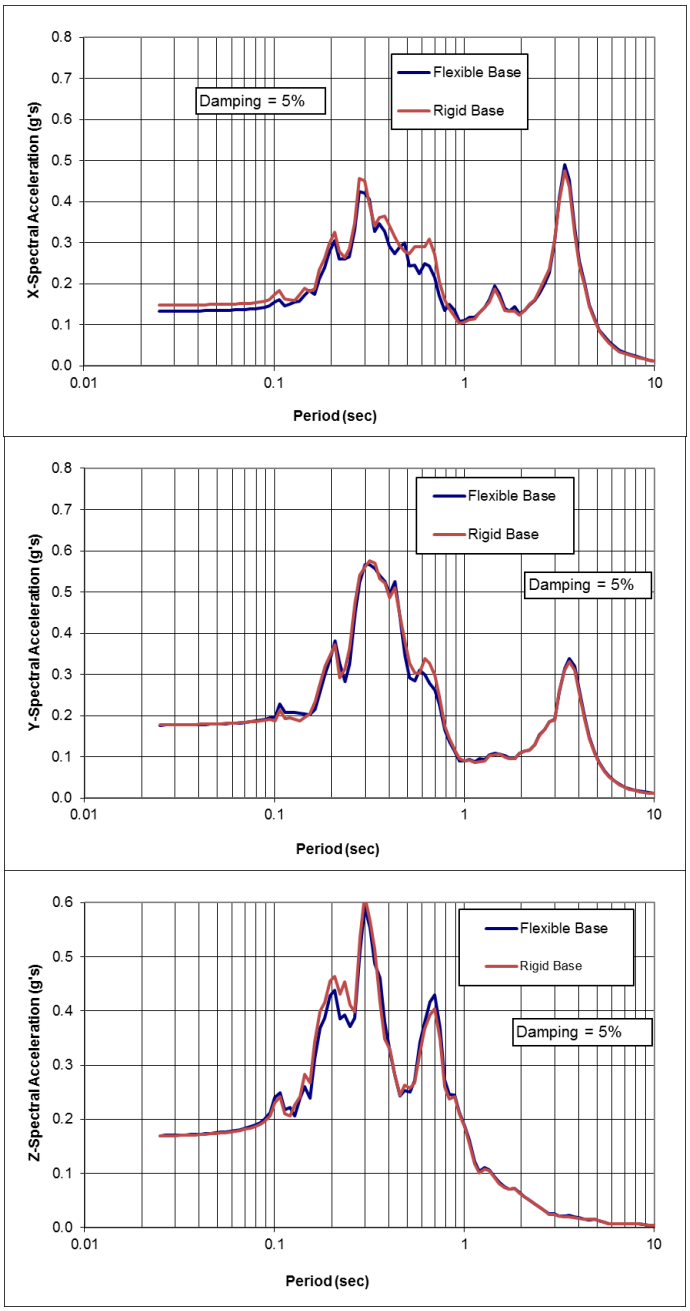

Figure 6. Comparison of SSI Response Spectra at Top of SGS Columns (FLEXIBLE AND Rigid Base)

SSI KMC (Impedance) Method

The interaction between the SGS foundation and the foundation sediments was modeled following the sub-structuring method developed by Kausel et al. [8]. Foundation dynamic impedance properties in terms of spring, mass and dashpot (KMC) parameters for the SGS foundation were developed using MTR/SASSI. The frequency dependent impedance properties were calculated for "One Pad" and "Four Pads" models each analyzed for four soil cases summarized in Table 1 and for two earthquake levels (ELE and ALE), making a total of eight analysis cases.

The "One" pad model was subjected to a unit harmonic force of 1N applied individually in the horizontally and vertically directions to the single pad model to develop translational stiffness properties in the x- (or y-) and z-directions, respectively. A unit moment of 1 N-mm was applied about the center of the "One pad" model to develop rotational stiffness properties about the x-axis (or y-axis). The "Four Pads" model consisted of the four foundation pads, where each pad has been loaded in a similar fashion as that in the "One Pad" model. The model used can be seen in Figure 7. The response of the "One Pad" and "Four Pads" models is extracted by outputting analyses results from the center of each foundation pad. In the "One Pad" model, results from only one node were extracted; for the model with four foundation pads, results from four nodes (corresponding to the centers of each single foundation pad) were extracted to develop a 6x6 flexibility matrix including the coupling terms with respect to frequencies. The foundation impedance functions were obtained by inverting all the 6x6 flexibility matrices. From these results, stiffness matrices with complex number entries were developed for multiple frequencies. From the stiffness matrices, real components represent the foundation dynamic stiffness, K, and the imaginary components represent the combined foundation material and radiation damping, ωC and imaginary components were extracted. For illustration purposes the impedance functions in the x and z directions are shown in Figure 8. The difference between "one" and "four" pads can be seen in Figure 8. Similar functions were calculated in the other degrees of freedom (not shown).

While the MTR/SASSI methodology can accommodate frequency dependent impedances when calculating the dynamic response most other dynamic analysis software requires the use of a constant frequency independent spring and dashpot. This is achieved by linearization of the real and imaginary parts of the impedance functions. For the analysis presented in this paper, as shown in Figure 8, it can be seen that the stiffness term does not vary greatly in the range of frequencies of interest, 0 to 5 Hz and can be assumed constant. The linearization consisted of selecting the static value of stiffness. (i.e. K_o and setting M to zero). The example shown in Figure 8, represents the case for LB rock and LB soil and ELE input, as detailed in Table 1. For this example case the following constant stiffness values for the foundation are obtained:

$K_{o,x}$ = 7,612 MN/m, $K_{0,y}$ = 7,505 MN/m, $K_{0,z}$ = 15,490 MN/m, $K_{0,xx}$ = 1.31E6 MN-m/rad and $K_{0,yy}$ = 1.29E6 MN-m/rad.

In some cases the stiffness is more strongly dependent on frequency and sometimes resulting in negative stiffness. Incorporating this stiffness in most software would require the use of a constant stiff and the addition of a fictitious virtual mass (M) term to the same node where the springs are attached to the structure. M is selected using the least square fit of (K_0-ω^2M) to the real component of the impedance function at the frequency of interest. In this paper M is set to zero.

The linearization for the imaginary part of impedance function consisted of obtaining a best linear fit ωC to this function, where $\omega=2\pi f$ (f is the frequency in Hz) and C is a constant. This constant C is determined by the least square fit between a frequency range of interest, which in this case is between 0 Hz and 5 Hz. The value assigned for C represents the radiation damping characteristics of both "One Pad" and "Four Pads" models. The final linearization for each case can be seen in Figure 8. The damping values for this example case were:

$C_{o,x}$ = 250 MN-s/m, $C_{0,y}$ = 300 MN-s/m, $C_{0,z}$ = 540 MN-s/m, $C_{0,xx}$ = 1.46E4 MN-m-s/rad and $C_{0,yy}$ = 1.58E4 MN-m-s/rad.

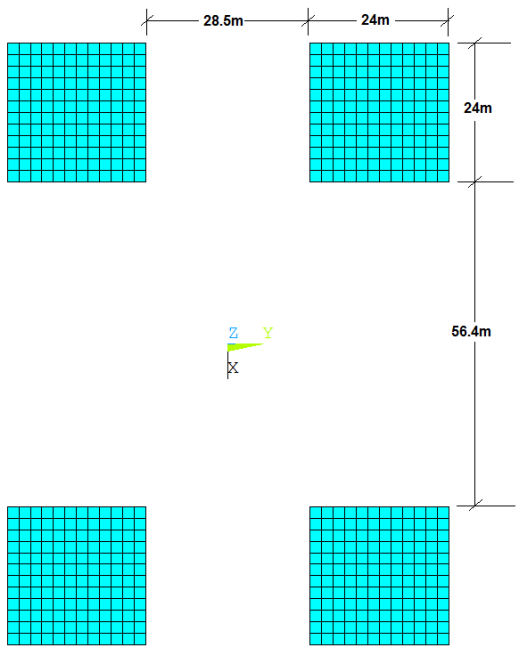

Figure 7. "Four Pad" Foundation Model for KMC

The value of C represents a viscous dashpot term that is attached to the structure and should not be confused with material damping. The structural material damping is represented by the complex shear modulus for the material, G*, defined by the following equation:

$$G^* = G\left(1 - 2\beta^2 + 2i\beta\sqrt{1 - 2\beta^2}\right) \qquad (1)$$

where G is the element material shear modulus and β is the material critical damping ratio. This method allows the damping to vary for different elements (materials). This is particularly useful in SSI systems in which the material damping in the structure and the soil is different, or if the structure is composed of different materials such as concrete and steel.

The way different dynamic analysis programs model damping varies depending on the procedure used to solve the dynamic equation of motion. While SASSI can accurately incorporate both the effects of frequency dependency and viscous damping, most time domain programs cannot. For this project there was a need to analyze the structure using different commonly used software. For design of the topsides SACS [13] was used, for design of the SGS it was preferable to use ANSYS [12]. In addition CAPFOS [14] and SAP2000 [15] were used for assurance purposes. The best approach to use in SSI analysis for each program is described below.

RESPONSE SPECTRUM ANALYSIS

The industry preferred method of seismic analysis and design is the response spectrum analysis (RSA). In this section the assumptions required for performing RSA in SACS, ANSYS, CAPFOS and SAP2000 are presented and key results obtained from the three methods are compared. Results from time history methods are detailed later in this paper.

SACS RSA SSI Model

The simplified SASSI model was converted to a SACS model. Various comparisons were performed to validate the conversion. SACS is a popular program that is often used for the analysis and design of offshore structures. The static springs previously defined from the foundation impedance analyses were used. For damping, dashpots cannot be used directly in SACS. The program requires either a constant damping for all modes or modal damping that varies per mode. Various damping values (including modal damping that changed with frequency) were tried and the results were compared with MTR/SASSI results. It was concluded that a constant modal damping value for each soil case was sufficient and that additional refinement of the damping values did not significantly improve the results. For ELE a constant modal damping of 5% for LB soil and 3% for UB soil were used. This damping is higher than the expected structural damping which for ELE was 2%. It should be noted that the design spectra were developed for 5% damping. Response spectra for other damping values (β %) in the range of 0.5% to 20% were calculated using the following equation as recommended in the seismic hazard analysis study:

$$S_{aH}(T, \beta\%) = [S_{aH}(T, 5\%)] \times \left[\frac{\{2.31 - 0.41\ln(\beta\%)\}}{1.65}\right] \qquad (2)$$

ANSYS RSA SSI Model

The conditioned SACS model was converted to an ANSYS simple beam model. This included converting members to equivalent beam elements, plates to 4-node shell elements, and related section and material properties from SACS to ANSYS format. Offset members were connected from their offset positions to the original work-points with rigid elements. Loads applied to model beam member density, equipment loads, etc., were converted to nodal forces and masses. Buoyancy loads, entrapped mass, hydrodynamic mass, and other loads and masses that were automatically calculated by SACS were manually calculated and added to the ANSYS model. The ANSYS model contained all retained DOFs.

The same SSI springs applied in SACS were used in the ANSYS model. SSI damping can be modeled as constant modal damping or modal damping that varies per mode. ANSYS also has the option of specifying SSI damping as a dashpot and computing the composite modal damping. Structural damping was assigned to each zone in the model. For the ELE, it was 2% for the SGS and topsides and 1% for the boom. The program then calculated the appropriate composite damping for each mode.

CAPFOS RSA SSI Model

The SACS model was converted to CAPFOS using the CAPFOS software. The CAPFOS model retains all DOFs as dynamic DOFs. The same SSI springs as in SACS were used. SSI damping was modeled as constant modal damping. The program can also specify modal damping that varies for each mode. CAPFOS was used for assurance to validate the SACS results

SAP2000 RSA SSI Model

The simplified MTR/SASSI model was converted to SAP2000. The model was validated by comparing the fixed base modes with the fixed base ANSYS model. The same SSI springs presented above were used in the SAP2000 model. Modeling of SSI damping is similar to ANSYS. The most appropriate method for modeling damping for SSI with SAP2000 is to input the damping as viscous dashpots and the program will calculate the composite modal damping. The calculated composite damping varied from 2 percent (assumed ELE structural damping) to 27 percent for modes associated with strong SSI effects.

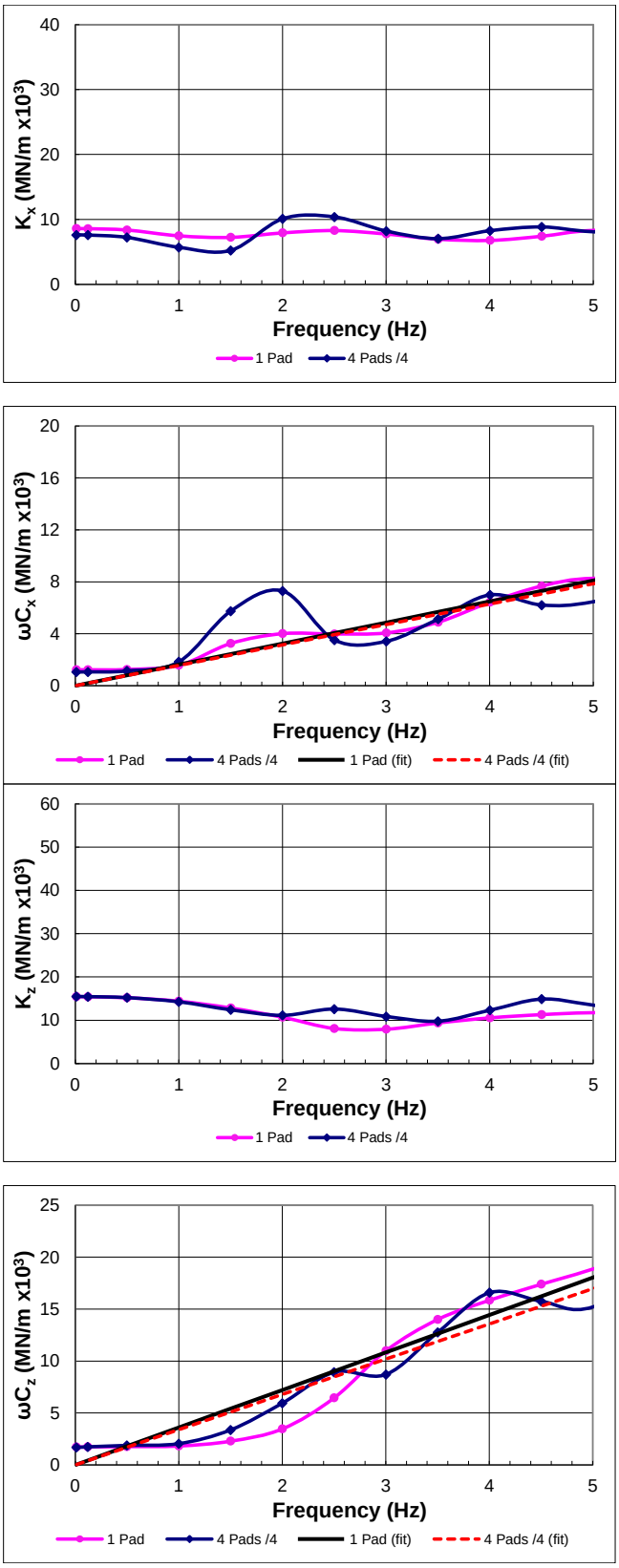

Figure 8. Dynamic Impedance Functions for "One Pad" and "Four Pads" Foundation Model (LBLS)

Modal (Eigen) Analysis

The first step of the RSA was to calculate the modes and mode shapes. The ANSYS or CAPFOS software retain all DOFs as dynamic DOFs when calculating the modes. A review of the SACS results showed that frequencies and mass participation factors were highly sensitive to the number of nodes with retained DOFs. It was observed that if a suitably large number of dynamic DOFs were not retained in SACS; critical modes were missed and resulted in erroneous dynamic responses when compared to ANSYS or CAPFOS. As more dynamic DOFs were retained in SACS the results approached those calculated by ANSYS and CAPFOS. In SACS the specification of retained DOFs is up to the user. It is essential that a sufficient number of DOFs are retained when calculating the modes and mode shapes to insure accurate dynamic results.

SAP2000 has two options for this step; standard modal analysis or Ritz analysis. The advantage of the Ritz method is that fewer modes are required to capture a sufficient percentage of the dynamic mass participation.

The modal analysis results are summarized in Table 3. In general there is good comparison in the modal frequencies obtained using SACS, CAPFOS, ANSYS and SAP2000. The corresponding mode shapes for the first 23 modes were also in good agreement. With SAP2000 the frequencies were calculated using standard Eigen value solver as well as Ritz vectors. The total modal participation factor from the four programs is shown in Table 4. It can be seen that in ANSYS and CAPFOS with 1000 modes extracted, 100 percent participation is not achieved, while with SAP2000 and Ritz method, 100 percent participation in all three directions is reached with 200 modes. This is one of the main advantages of the Ritz method [16].

Table 3. Modal Analysis Results Comparison

SACS		CAPFOS		ANSYS		SAP2000		
MODE	Freq. (Hz)	MODE	Freq. (Hz)	MODE	Freq. (Hz)	MODE	Freq. (Hz)	Ritz (Hz)
1	0.392	1	0.405	1	0.395	1	0.397	0.397
2	0.398	2	0.413	2	0.402	2	0.405	0.405
3	0.449	3	0.461	3	0.449	3	0.453	0.453
4	0.703	4	0.707	4	0.705	4	0.707	0.707
5	0.726	5	0.734	5	0.738	5	0.739	0.739
6	1.321	6	1.371	6	1.307	6	1.338	1.338
7	1.434	7	1.491	7	1.433	7	1.491	1.491
8	1.443	8	1.506	8	1.464	8	1.506	1.506
9	1.459	9	1.531	9	1.478	9	1.536	1.536
10	1.514	10	1.57	10	1.523	10	1.549	1.549
11	1.555	11	1.635	11	1.587	11	1.632	1.632
12	1.579	12	1.668	12	1.632	12	1.668	1.668
13	1.609	13	1.698	13	1.641	13	1.693	1.693
14	1.63	14	1.715	14	1.675	14	1.714	1.714

15	1.682	15	1.727	15	1.712	15	1.782	1.782
16	1.705	16	1.753	16	1.75	16	1.808	1.808
17	1.802	17	1.766	17	1.78	17	1.883	1.883
18	1.864	18	1.864	18	1.785	18	1.906	1.906
19	1.876	19	1.915	19	1.86	19	1.937	1.937
20	1.905	20	1.923	20	1.873	20	1.976	1.976
21	1.931	21	1.958	21	1.908	21	2.038	2.038
22	1.961	22	1.984	22	1.92	22	2.072	2.072
23	1.991	23	2	23	1.962	23	2.075	2.075
….		….		….		….		
200	10.81	999	17.85	1000	14.76	200	5.714	315.6

Table 4. Modal Participation Factor S

		X-Dir. (%)	Y-Dir. (%)	Z-Dir. (%)	# of modes
SACS		91	91	76	200
CAPFOS		92	92	83	999
ANSYS		97	99	74	1000
SAP2000	Ritz	100	100	100	200
	Eigen	97	97	66	200

RSA Results

Maximum accelerations computed using RSA are compared with the base MTR/SASSI results in Table 5. The accelerations were calculated at the top of the SGS legs and the topsides top deck corners (average of four locations). The first set of results were obtained from MTR/SASSI using time history analysis. The second set are from SACS assuming constant 3 percent damping for all modes, the third and fourth sets are SAP2000 using 2 percent structural damping plus SSI damping (composite). The third set of results were for a response spectrum input that was calculated directly from the time history used as input in MTR/SASSI, referred to as NRWR, while the input used in the fourth set was the design spectrum scaled to 3 percent damping. Important differences were observed when comparing the design spectrum to the spectrum calculated directly from the spectrally matched time histories. The differences were significant at 2 and 3 percent damping. The table also shows the ratio of the calculated RSA acceleration to the target MTR/SASSI value. In general the SACS results which are used for design envelope the target results. Additionally, as to be expected better match is obtained when the response spectrum is calculated directly from the time history for the applicable damping rather than using the target design spectrum.

TIME HISTORY ANALYSIS

In addition to the RSA described above, the ALE alignment was also performed using time history analysis (THA) method. The target solutions were generated using MTR/SASSI. The THA analyses were performed using ANSYS, CAPFOS and SAP2000. The assumptions to implement SSI effects in each program are described below.

ANSYS THA SSI Model

The same RSA ANSYS model was used for the THA. The SSI spring values are the same as above. SSI damping was modeled as a viscous dashpot. For the ALE the MTR/SASSI model assumed a structural damping of 3% for the SGS and topsides and 2% for the flare boom. To model this difference in the ANSYS THA model equivalent Rayleigh damping was used to specify the structural damping. Different Beta factors were specified for the flare boom elements to reflect lower damping. The resulting damping curves are shown in Figure 9. It can be seen that for frequencies compatible with the main structural modes, the damping value are close to the target structural damping. The dynamic response was calculated using the direct integration method.

CAPFOS THA SSI Model

The CAPFOS THA was performed using direct integration and the same modeling assumptions as in ANSYS.

SAP2000 THA SSI Model

SAP2000 incorporates several methods for dynamic time history analysis. For this comparison The Ritz method with the Fast Nonlinear Analysis method (FNA) was used to calculate the time history response, Wilson [16]. The SSI damping was modeled directly as linear viscous dashpots. Structural damping was modeled as modal damping, 3% for the SGS and topsides and 2% for the flare boom.

Table 5. Comparison of RSA Maximum Accelerations (g) with MTR/SASSI Results for ELE

Location	MTR/SASSI Results (1)			SACS (2)		
	x-dir.	y-dir.	z-dir.	x-dir.	y-dir.	z-dir.
Top of SGS leg stub	0.171	0.219	0.126	0.278	0.289	0.163
Topsides top deck (corner)	0.142	0.159	0.141	0.167	0.158	0.178
				Ratio (2)/(1)		
Top of SGS leg stub				1.63	1.32	1.32
Topsides top deck (corner)				1.17	0.99	1.28
Location	SAP2000 RS (NRWR) (3)			SAP2000 RS (Design) (4)		
	x-dir.	y-dir.	z-dir.	x-dir.	y-dir.	z-dir.
Top of SGS leg stub	0.177	0.188	0.141	0.141	0.149	0.110
Topsides top deck (corner)	0.141	0.151	0.152	0.117	0.107	0.112
	Ratio (3)/(1)			Ratio (4)/(1)		
Top of SGS leg stub	1.04	0.87	1.14	0.83	0.68	0.91
Topsides top deck (corner)	1.00	0.83	1.08	0.82	0.68	0.86

Time History Analysis Results

The base shear, vertical force, overturning moment and twisting moment calculated using RSA and THA are compared in Table 6 with the base MTR/SASSI (Column 1) results for URUS and ELE input. Column 2 are the results for MTR/SASSI where SSI is modeled with

KC, column 3 are the ANSYS time history results, column 4 are the SAP2000 time history results and column 5 are the SACS RSA results. Additionally the ratios of the calculated values to the base MTR/SASSI case are shown in Table 6. As expected the MTR/SASSI results with KC align within 5 percent of the base case. The other three methods are also within 15 percent of the base case with some values being under predicted.

Maximum accelerations computed using THA are compared with the base MTR/SASSI results in Table 7. The accelerations were calculated at the top of the SGS legs and the topsides top deck corners (average of four locations). The first set of results were obtained from MTR/SASSI using time history analysis. The second set are from SAP2000 THA. The third set of results are the same SAP2000 RSA results reported in column 3 of Table 5. Table 7 also shows the ratio of the calculated SAP2000 accelerations to the target MTR/SASSI values. In general the SAP2000 accelerations are within 10 percent of the target accelerations.

Table 6. Base Shear and Base Moments for URUS

	MTR/SASSI		(2)/(1)	ANSYS	(3)/(1)
	Layered	with KC		with KC THA	
	(1)	(2)		(3)	
Base Shear - x (kN)	238,009	248,883	1.05	215,600	0.91
Base Shear - y (kN)	219,733	228,802	1.04	219,600	1.00
Axial Force - z (kN)	128,497	125,435	0.98	103,000	0.80
Overturning M_{xx} (kN-m)	6,636,911	6,975,768	1.05	6,345,000	0.96
Overturning M_{yy} (kN-m)	4,686,992	4,501,944	0.96	4,343,000	0.93
Twisting Mzz (kN-m)	1,304,479	1,312,956	1.01	1,102,000	0.84

	SAP2000 with KC THA	(4)/(1)	SACS with K RSA	(5)/(1)
	(4)		(5)	
Base Shear - x (kN)	246,703	1.04	248,000	1.04
Base Shear - y (kN)	224,546	1.02	261,000	1.19
Axial Force - z (kN)	114,597	0.89	128,000	1.00
Overturning M_{xx} (kN-m)	6,444,443	0.97	5,630,000	0.85
Overturning M_{yy} (kN-m)	4,378,367	0.93	4,930,000	1.05
Twisting Mzz (kN-m)	1,483,195	1.14	-	-

Table 7. Comparison of THA Maximum Accelerations (g) with MTR/SASSI Results for ELE

Location	MTR/SASSI (1)			SAP2000 THA (2)			SAP2000 RSA (3)		
	x	y	z	x	y	z	x	y	z
Top of SGS leg stub	0.17	0.22	0.13	0.17	0.20	0.12	0.18	0.19	0.14
Topsides top deck corner	0.14	0.16	0.14	0.13	0.14	0.13	0.14	0.15	0.15
				Ratio (2)/(1)			Ratio (3)/(1)		
Top of SGS leg stub				1.0	0.89	0.93	1.04	0.87	1.14
Topsides top deck corner				0.91	0.90	0.94	1.00	0.83	1.08

In general using an SSI analysis approach that is implemented in SASSI is the most appropriate method for SSI analyses since the dynamic soil stiffness is rigorously modeled in the frequency domain and variable material damping can be properly represented. However the results from various software packages were compared to the base case results. Each alternative program has analysis limitations to solve a KMC gravity base foundation problem. The objective was to envelop the MTR/SASSI results without being too conservative. While this was in general possible it was not achievable in all areas.

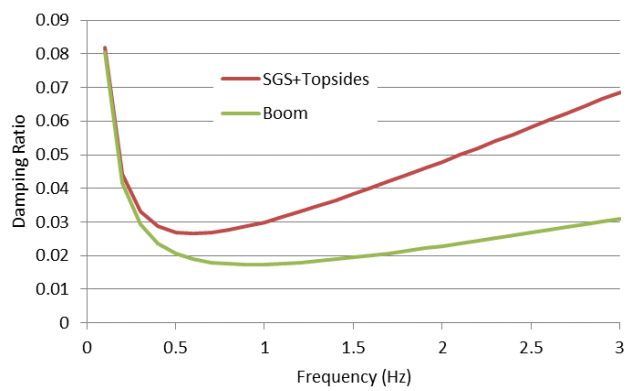

Figure 9. Rayleigh Damping Curves for ALE

SEISMIC LOADS FOR EQUIPMENT AND PIPING

One notable issue investigated in this study is how to best facilitate proper inclusion of local dynamic amplifications from the supporting superstructure in the seismic design of topsides equipment, appurtenances, & piping. The topsides equipment and piping design is normally performed by mechanical discipline personnel with minimum interfacing with civil/structural personnel. However, calculation of the seismic loads is usually generated by civil/structural discipline, especially if SSI analyses are included. Topsides equipment and piping loads can be specified as quasi-static accelerations or preferably in the form of floor response spectra generated directly from the SSI model to properly account for structural global dynamic amplifications. Without proper interfacing between disciplines, topsides equipment and piping systems may end up being designed for unconservative seismic loads.

CONCLUSIONS

SSI analyses were performed for a steel gravity structure using a number of different software and various impedance-based KMC methods. Benchmark results were calculated with MTR/SASSI software using the flexible volume substructuring method in the frequency domain for alignment. The following conclusions were derived:

- The dynamic response of large gravity-based structures should incorporate SSI effects even in moderate seismic zones to achieve a more optimized foundation design and avoid the potential for unconservative design of the superstructure and topsides equipment and piping.
- When detailed design models are simplified for SSI analysis or converted for input to other computer programs it is essential to align the results by comparing the fixed-base response obtained from the different models. The fixed-base results can also be used to better understand the effects of SSI.
- Initial SSI investigations should include sufficient details prior to accepting any simplifications, such as the assuming a rigid base

slab or ignoring interaction between multiple foundation pads through the soil.

- When performing modal superposition analysis some programs retain all DOFs with mass as dynamic DOFs while other programs, such as SACS, require the user to specify the retained DOFs. Erroneous and unconservative responses may results if an adequate number of DOFs in appropriate locations are not retained.
- It is essential to check the design of secondary systems using properly calculated floor response spectra. In most situations in moderate seismic zones, seismic loads may control the design of equipment and piping especially safety components needed for safe shutdown following an ALE event.
- In general, it is preferable to use a detailed SSI analysis approach such as the one implemented in SASSI because the dynamic soil stiffness is rigorously modeled in the frequency domain and variable material damping can be properly represented. For the design of large structures, however, it may be necessary to use other software packages that use the KMC method and RSA in which case it is necessary to understand the limitations of each program and to align the results with the more detailed calculations performed using a more comprehensive SSI methodology such as MTR/SASSI. With proper alignment, it is possible to manage the various limitations of the software while maintaining adequate margins for design. This conclusion may not be applicable to more complicated soil profiles or when the dynamic response of the soil/foundation/structure is strongly nonlinear.

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