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Dynamic Analysis of Modular Structures Considering Soil - Pile - Structure Interaction

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Abstract. *Advanced method of soil-pile-structure interaction is introduced in the dynamic analysis for modular structures in order to design cost-efficient foundations and structures. The dynamic analysis is divided into two stages for simplification purposes. In the first stage, a simplified analysis is performed to optimize the piling and foundation layouts. The simplified FEM models are then validated to ensure reliability of analysis. In the second stage, a detailed superstructure model is evaluated to check for excessive local vibration within the structure. A typical steel frame module in the scope of this study is 54 m long, 14.7 m wide and 35 m tall with a total weight of approximately 4,000 metric tons. The modules are supported on concrete piled foundation, with 15 m long 400 mm square precast concrete piles, situated in highly variable soil conditions. The radiation damping (geometric damping) of soil-pile system mainly governs the vibration of foundation and structure. The stiffness and damping of piled foundation are generated frequency dependent. Then, the impedances of piled foundation are imported to the FEM model as boundary conditions. The dynamic response of the structure is calculated using time history analysis and steady state analysis. Different design options of piled foundation are compared in order to optimize cost and to meet the allowable machine vibration and human perception limits.*

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1 INTRODUCTION

In recent years, pre-fabricated steel modular structures have become widely used for the large projects in energy and chemical industries to save cost and improve safety during construction. One project is an expansion of existing facilities situated in Tengiz, western Kazakhstan. Modular structures are pre-fabricated in Republic of Korea, and then sea-transported to the project site. A wide verity of vibrating equipment is mounted into the steel modules, such as compressors, turbines, pumps and motors. Both of centrifugal and reciprocating machines are included, some of them operating in low speed and some in high speed. The large vibrating equipments are involved, and around 30 modules are identified as critical and detailed dynamic analysis to be required.

With the soil-pile-structure interaction, the effect of soil properties is important to the dynamic behavior of foundation and structure. The varied soil profiles are found from the detailed geotechnical report. The soil is soft in the shallow depth, and the shear wave velocity is measured to be less than 100 m/s in some locations. So the dynamic analysis is complex and challenging in this project.

The advanced method of soil-pile-structure interaction is introduced in dynamic analysis for modular structures in order to design cost-efficient foundations and structures. For simplification purposes, dynamic analysis is divided into two stages. In the first stage, a simplified analysis is performed to understand the dynamic behaviour of the structure and the resistance offered by foundation impedance. In the second stage, a detailed superstructure model is evaluated to check for excessive local vibration in critical areas which are more remote from the machine. The frequency dependent impedances (stiffness and damping) of pile foundation generated from DYNAN software are imported to the FEM models as boundary conditions. The radiation damping (geometric damping) of soil-pile system primarily governs the vibration of foundation and superstructure.

2 SOIL-PILE-STRUCTURE INTERACTION

Many researchers have made contributions to the subject of soil-pile-structure interaction, such as Dobry & Gazetas [1], Roesset et al [2], Gazetas & Makris [3], and Wolf [4]. Recent alternative approaches have been developed on this subject, such as analytical model based on homogenization methods by Boutin & Soubestre [5]. Macro-elements are used to model the soil-pile system by Li et al [6]. Different approaches are available to account for dynamic soil-pile interaction but they are usually based on the assumptions that the soil behavior is governed by the law of linear elasticity or visco-elasticity, and that the soil is perfectly bonded to a pile. In practice, however, the bonding between the soil and the pile is rarely perfect, and slippage or even separation often occurs in the contacted area. Furthermore, the soil region immediately adjacent to the pile can undergo a large degree of straining, which would cause the soil-pile system to behave in a nonlinear manner. Various numerical approaches are used to model the soil-pile interaction, such as the finite element or boundary element methods. However, the problem is too complex, especially for a group with large number piles in non-linear soil. A rigorous approach to the nonlinearity of a soil-pile system is extremely difficult and time consuming.

As an approximate analysis, the procedure is developed using a combination of the analytical solution and the numerical solution, rather than using the general FEM. This procedure is considered as an efficient technique for solving the nonlinear soil-pile system. The relationship between the foundation vibration and the resistance of soil layers around the pile was derived using elastic theory by Baranov [7]. Both theoretical and experimental studies have shown the dynamic response of piles to be very sensitive to the properties of the soil in the vicinity of the pile. Velestsos and Dotson [8] proposed a scheme that can account for the mass of the boundary zone. Some of the effects of the boundary zone mass were investigated by Novak and Han [9], who found that a homogeneous boundary zone with a non-zero mass yields undulation impedance due to reflections of stress wave from the fictitious interface between the two media. A model for the boundary zone with a non-reflective interface was proposed. The soil in boundary zone has properties smoothly approaching those of the outer zone to alleviate wave reflections from the interface. The details of constitutive model have been described by Han & Sabin [10], not repeated herein. The modulus ratio G_i/G_o is an approximate indicator for the nonlinear behavior of soil. The value of the modulus ratio depends on the method for pile installation, the density of excitation and vibration amplitudes. Further dynamic tests on piles are needed to determine the value of the modulus ratio. The model of the boundary zone with a non-reflective interface has been applied in practice to solve the problem in many projects. However, the method is not a rigorous approach to model the nonlinearity of a soil-pile system. It is an equivalent linear method with a lower value of G_i and a higher value of damping β_i in the boundary zone. With such a model, analytical solutions can be obtained for the impedance functions of a pile, and the software DYNAN [11] was developed based on this approach.

The group effect of piles is accounted for by using the method of interaction factors. The static interaction factors are based on Poulos and Davis [12]. The dynamic interaction factors are derived from the static interaction factors multiplied by a frequency variation, and the frequency variation of interaction factors is based on the charts of Kaynia and Kausel [13]. There are six degrees of freedom for the rigid mat, and lateral vibration is coupled to rocking vibration. The foundations (or caps on piles) are assumed to be rigid. However, in most cases, the superstructures and foundations are flexible rather than rigid. The effects of soil-pile-structure interaction on dynamic response of machine foundations were discussed by Han [14]. The dynamic response of the superstructure can be calculated by FEM models using software SAP 2000 [15].

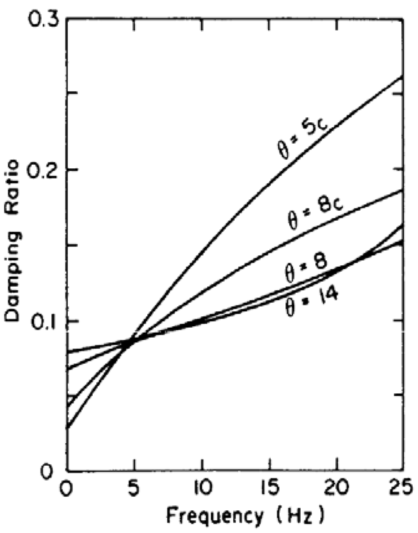

Figure 1: Horizontal damping ratio of pile

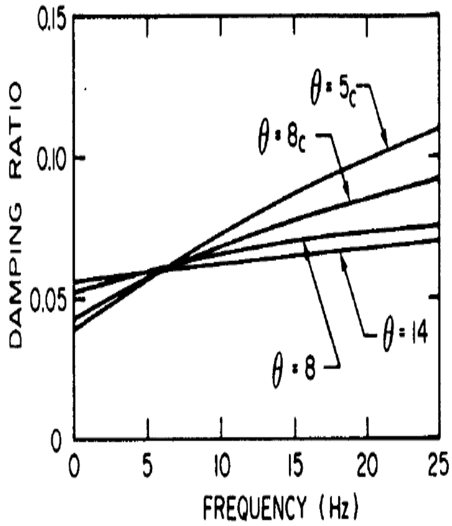

Figure 2: Rocking damping ratio of pile

The radiation damping is the dominant energy dissipation mechanism in most dynamically loaded foundation systems, and also in seismic response. The elastic-wave energy from foundation vibration dissipated infinitely far away in three dimensions to form the radiation damping. The formula of radiation damping is derived based on elastic theory in which the soil is assumed to be a homogeneous isotropic medium. As a matter of fact the soil is not a perfectly linear elastic medium it is assumed to be. It is a recognized fact in the field of soil dynamics that the damping is overestimated with the elastic theory. The values of radiation damping have been modified and reduced in the application based on the measurements found in practice. To validate the soil-structure interaction, a series of dynamic experiments have been done on full-scale piles, see El-Marsafawi et. Al [16]. The vibration measurements were done on group piles in the field to confirm the theoretical values modified for applications, see Han and Yang [17].

The damping ratios were calculated based on the measurements from a dynamic test of steel pile in the field, as shown in Figure 1 for horizontal vibration, and Figure 2 for rocking vibration, see Han and Novak [18]. The harmonic excitation loads applied to the pile cap from low frequency to high frequency (25 Hz) with different levels of excitation intensities, where the curves are marked by θ to identify the different values of the dynamic loads. As the bottom of pile cap connected to the ground surface, the excitation intensity is marked by θ = 5c and 8c. As the bottom separated from ground surface, the excitation intensity is marked by $\theta = 8$ and 14. It can be seen that the radiation damping increases with the frequency, and the damping ratio increased from 0.05 to 0.25. The nonlinear properties of soil shown with the excitation intensities increased in this case.

3 SIMPLIFIED MODEL FOR DYNAMIC ANALYSIS

Execution of complex three dimensional dynamic analyses can be a complicate, time consuming and computationally demanding process. Engineers are often challenged to develop practical and simplified methods of analysis, capable of producing accurate and reliable results. Ongoing design changes to layout of modules and their foundations required continuous execution of dynamic analysis; ensuring structural service requirements for large vibrating equipment have been met. It was therefore necessary to develop a practical simplified model that could produce consistent and reliable results within reasonable analysis duration and computational effort. Consequently, the dynamic analysis was broken down into two individual stages. In the first stage the adequacy of the module and foundation layout were verified against vendor requirements for the displacement amplitudes at machine skid supports.

To undertake this analysis, a simplified model was developed to capture dynamic soil-structure interaction of the module structure and foundation system. In this simplified model, module foundation was modeled completely with the base frame of the steel structure where the vibrating machinery is mounted. Pile impedance has been modeled using frequency dependant links, assigned at each pile location, with pile impedance calculated using DYNAN software. Dynamic loads applied to the system were assigned to several nodes, modeled at locations corresponding to centers of gravity (CG) for bearings of the high-speed rotating compressor and related motor. To simulate mounting of equipment skids on the module base frame, nodes representing equipment bearing CGs were connected to the module base frame with a series of rigid links, each representing equipment skid support anchor. For simplification purpose and to minimize computing time, majority of the module superstructure has not been explicitly modeled as seen in Figure 3.

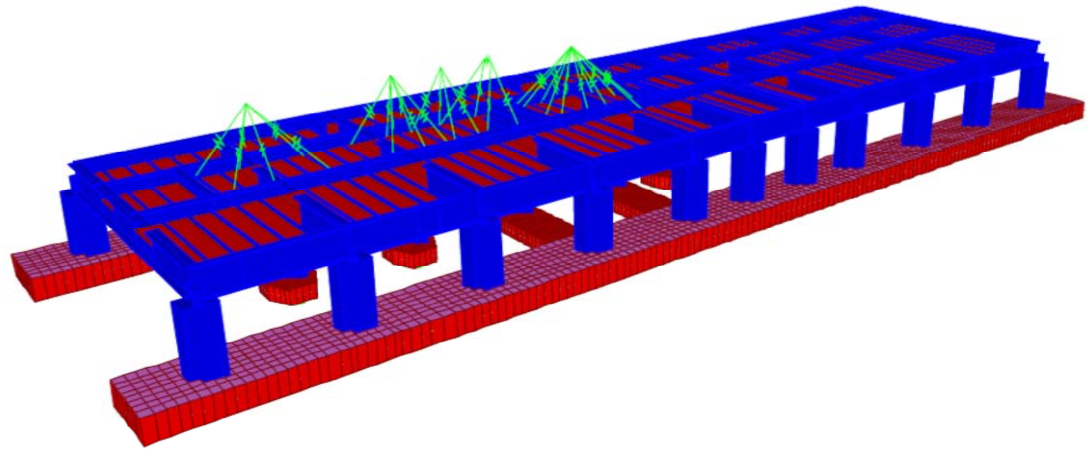

Figure 3: Model of foundation and mounted vibrating equipment for first stage analysis

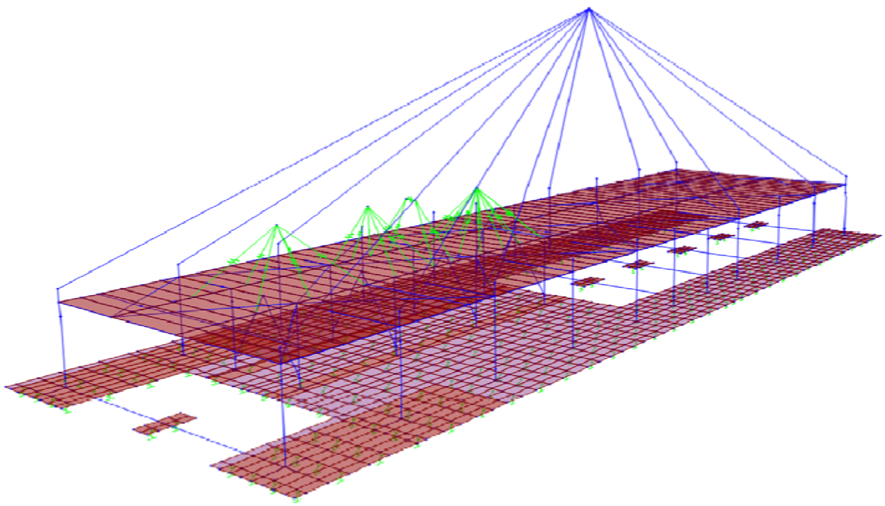

Figure 4: Effects for CG of steel frame located at the real elevation

To account for modal mass of the structure in analysis, individual point loads of equivalent gravity load have been assigned at primary column locations on the module base frame. Initial trial analyses have shown that this approach is consistently capable of producing reliable results, similar to complex models that account for entire module structure. Results suggested that stiffness of the superstructure remote from dynamic load application points and inertia forces generated by the superstructure under dynamic load have an insignificant contribution to dynamic response at module base where equipment is situated. To confirm the accuracy of analysis performed using this simplified model, an additional model was developed to capture stiffness of the superstructure and to apply modal mass at module centre of gravity. To simulate the behavior of the module superstructure, its mass and other dead loads acting on the module frame were lumped at the structure's center of gravity, modeled as a single node and connected to the module base frame using a set of links attached to nodes that correspond to primary column locations, as shown in Figure 4. The stiffness of the links was determined on the basis of the module frame stiffness. First, using the static analysis model,

Dynamic Force from Machine	Location	Max Amplitude (μm)			
		Lateral		Vertical	
		Simplified	Real	Simplified	Real
Motor (60 Hz)	Motor Bearing	10.680	9.356	14.506	11.894
	Gear Box (L)	6.304	3.688	0.849	0.761
	Gear Box (H)	6.154	3.678	0.767	0.636
	Compressor	5.900	4.120	1.695	1.919
Compressor (162 Hz)	Motor Bearing	0.017	0.049	0.009	0.003
	Gear Box (L)	0.893	0.547	0.188	0.109
	Gear Box (H)	0.823	0.558	0.120	0.164
	Compressor	0.658	0.488	0.209	0.141

Table 1: Comparison of dynamic response with different FEM models

the superstructure stiffness was evaluated by applying a notional transverse load near to the module CG, such as load of 100 kN. This notional load was then combined with module dead loads and static analysis was performed.

The comparison of dynamic response is shown in Table 1 with different FEM models. The original approach is a simplified model and shown as "Simplified". The model with CG of superstructure is equivalent to the real steel frame and shown as "Real". In the table, gear box (L) is at side of low speed and gear box (H) at side of high speed. It can be seen that the maximum amplitude in vertical direction is 14.506 μm for simplified model and 11.894 μm for real model. The dynamic response using the simplified model is close to that using the real model. In general, displacements obtained from the real model do not exceed those achieved using the simplified model. In fact, an overall trend shows a minor reduction in displacement amplitudes, thus showing the original simplified approach to be slightly more conservative in determining the dynamic response. This behavior can be primarily attributed to additional stiffness introduced into the system through provision of the stiff links connected to the module base frame. It is therefore logical to expect insignificant reduction in local resonance behavior. It can be concluded that the original assumption is valid. Simplification of the dynamic analysis model, by exclusion of the module superstructure from analysis and compensation of the modal mass at base frame level, has achieved a substantial reduction in computational time. This was achieved without causing any notable impact on the accuracy or the reliability of obtained results. Overall, modeling simplifications undertaken in the course of this study provided a practical yet accurate method of evaluating dynamic performance of large steel structures, subject to sustained dynamic loading.

4 DESIGN OF PILED FOUNDATION AND CHECKING VIBRATION OF STEEL FRAME

The typical modular structure is a steel frame with overall length of 54 meter, 16 meter wide and around 35 meter in height. The total weight of the modules is approximately 4,000 metric tons. This includes mechanical and electrical equipments, HVAC system, piping and structural steel and architectural features. The module carried many kinds of vibrating equipment and piping. An overall 3D model of the module is shown in Figure 5, supported on pile foundation.

A simple general practice is to limit the loading to half of allowable pile capacity under the vibrating equipment, to keep the dynamic behavior of soil-pile system in the linear elastic region. In this project, as detailed and qualified dynamic analysis have been carried out, and the vibration results obtained are based on the reliable values of radiation damping, the maximum load limit is raised reached to 70% of allowable pile capacity. Two bore holes placed in each location of module, and the average value of soil properties measured is used to generate the stiffness and damping. The FEM model for the first stage dynamic analysis is shown in Figure 6. The piles are presented by link element (stiffness and damping) and the machines by rigid links.

In order to meet permissible vibration amplitude and to optimize piling and foundation layout as well, various options or schemes have been analyzed as part of first stage analysis. This includes but not limited to changing number of piles, changing the size and arrangement of pile caps, changing the pedestal sizes, variation in modulus of elasticity, with and without water table consideration, variation in soil dynamic properties etc. The most important one is on optimization of total number of piles as this involves a lot of cost saving for foundation part. In an early option, the spacing of pile is 1.2 m based on three times of pile diameter, and total 312 piles are used. In another option the spacing is increased and total1 of 190 piles are used. It is interesting that the piling layout with 190 piles was found to be more efficient than the piling layout with 312 piles, and the group efficiency ratio increased from 0.10 to 0.15. Thus, it reduced 122 numbers of piles and saved a lot of cost. The summary of final results for pile layout optimization is given in Table 2. It can be seen that the maximum amplitude of foundation with 190 piles is 14.17 μm, meeting the vibration limit. The allowable vibration limit is 15.0 μm (peak-to-peak). The vibration of whole soil-pile-structure system is governed by the piles layout. It is interesting to note that some excessive vibration may be caused by the local structure and arrangement, rather than the entire piles. For example, the vibration can be reduced significantly in some location by added two small pile cap strips, as shown in Table 2. The local pile caps (tie beams) have been added at two grid lines as shown in Figure 6. The tie beams or pile cap strips helped to reduce the vibration a lot. It can be seen that the vertical amplitude would be 37.94 μm without the tie beams, much higher than the allowable limit. The dynamic response changed significantly by adding only two small local pile cap strips.

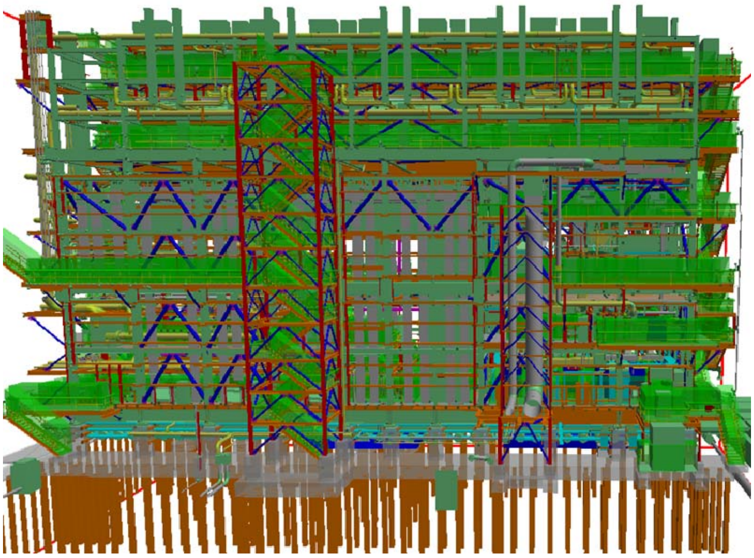

Figure 5 Module structure installed on pile foundation

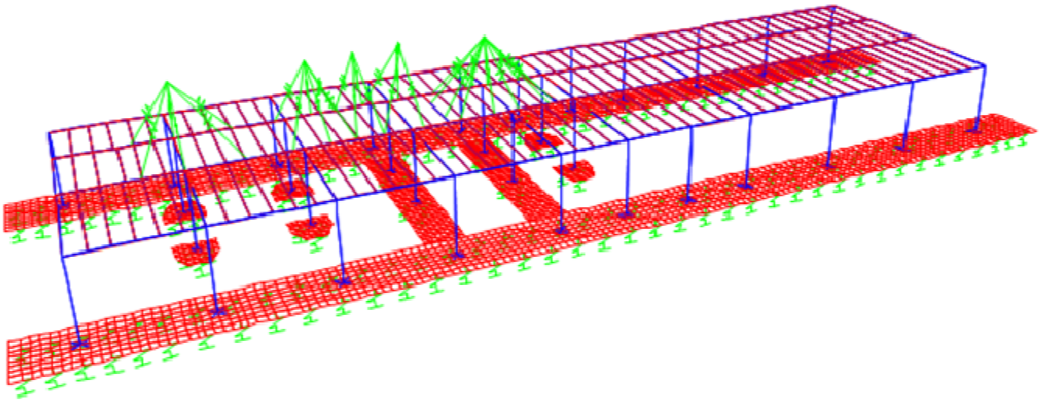

Figure 6 FEM model for Dynamic Analysis 1st Stage

Vibration Direction	Amplitude at Anchor Bolt Location (peak-to-peak, µm)								
	Pile layout – 312 piles			Pile layout- 190 piles with local tie beams			Pile layout without local tie beams		
	Motor (60 Hz)	Compressor (162 Hz)	TOTAL	Motor (60 Hz)	Comp (162Hz)	TOTAL	Motor (60 Hz)	Comp (162Hz)	TOTAL
Vertical	17.6	0.48	18.08	9.20	2.15	11.35	29.20	8.74	37.94
Lateral	10.60	0.70	11.30	13.90	0.27	14.17	13.70	0.20	13.90

Table 2 Dynamic response of foundation with different pile layout

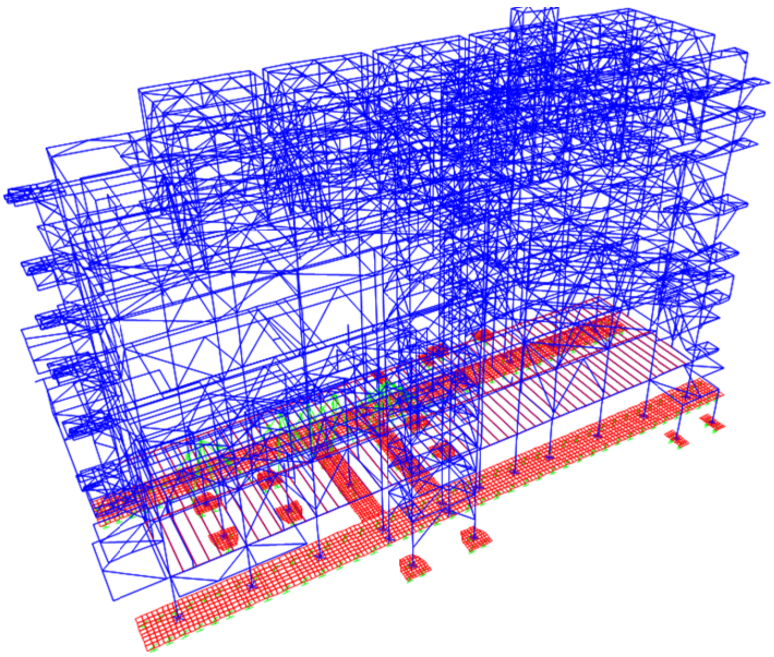

Figure **7** FEM model for Dynamic Analysis 2 nd Stage

Dynamic force from machine	Location of CG	Maximum amplitude (peak-to-peak, μm)			
		Lateral		Vertical	
		TH	SS	TH	SS
Motor (60 Hz)	Motor	16.6	18.3	1.4	9.3
	Compressor	15.6	4.4	0.68	5.1
Compressor (162 Hz)	Motor	0.15	0.8	0.19	1.3
	Compressor	0.37	2.6	0.25	2.4

Table 3. Comparison of dynamic response with different methods

The FEM model for the second stage dynamic analysis is shown in Figure 7. In this stage the local vibration of steel structure is checked, and no further change is done for the foundation part. This model is very detailed and includes almost every main structural elements, and including foundation part. Both free and forced vibration analysis were carried out to ensure that there is no excessive vibration which can cause discomfort to the personnel working in accessible area. The dynamic response is shown in Table 3 from the second stage, using time history analysis presented as TH and steady state analysis presented as SS in the table. The allowable vibration limit is 30 μm (peak-to-peak) at the location of machine CG. It can be seen that the maximum amplitude of 16.6 μm calculated by time history analysis and 18.3 μm by stead state analysis. The results of maximum response are close from the two methods. Large number vibration modes are involved for the complex steel structure, when using time history analysis. So it is suggested that the time history analysis is used for modules with lower speed vibrating equipment, and the steady state analysis is used for higher speed equipment.

CONCLUSIONS

- Dynamic analysis of pre-fabricated modular structures is a complicate, time consuming and computer-intensive process. The most optimal solution to undertaking it is splitting the analysis into two stages. In the first stage the dynamic analysis is concentrated on the pile foundation part based on a simplified model, and the mass of superstructure lumped at the bottom of columns. In the second stage the superstructure is checked by dynamic analysis to avoid any excessive vibration within the steel structure. The dynamic response from the simplified model is close to that from the real superstructure, and the results from the simplified model are reliable.
- Consideration of soil-pile-structure interaction in analysis can lead to optimization of foundation design, resulting in a more cost efficient design that meets the allowable vibration limits. The radiation damping of foundation is the dominant energy dissipation mechanism, and the values of damping are justified in the software based on dynamic tests.
- The vibration of the overall soil-pile-structure system is governed by the arrangement of the piles in the foundation, as indicated in the first stage dynamic analysis. However, some excessive vibration may be caused by the local structure and arrangement, rather than by the entire piles.

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