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DYNAMIC ANALYSIS FOR MODULAR STRUCTURE

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Abstract: 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, the dynamic analysis is divided into two stages in this study. In the first stage, simplified analysis is performed to optimize piling and foundation layouts. The simplified 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. The radiation damping (geometric damping) of soil-pile system mainly governs the vibration of foundation and structure. Frequency dependent stiffness and damping are generated by software DYNAN. Then, impedances of the 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.

1 INTRODUCTION

Recent years, the pre-fabricated steel modular structures are widely used for the large projects in energy and chemical industry, to save cost and improve safety during construction. One project is an expansion of existing facilities located in Tengiz, western Kazakhstan. The modular structures are pre-fabricated in Korea, then sea-transported to the 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 shallow depth, and the shear wave velocity is measured even to be less than 100 m/s in some locations. So the dynamic analysis is complex and challenged in this project.

To ensure a safe and reliable operation throughout the design life of equipment it is important to assess dynamic behavior of the supporting structure. It has been assured that the foundations and support structures for vibrating equipment is capable of withstanding the self weight of the machine as well as the dynamic forces induced by its operation and satisfy serviceability requirements including deflection limitations. Two particular aspects of dynamic response are studied: (1) peak vibration response (e.g., displacement, velocity) due to the unbalanced forces by equipment and (2) avoidance of resonance due to matching of the structural fundamental frequency and equipment operating frequency.

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, the dynamic analysis is divided into two stages. In the first stage, a simplified analysis is performed to optimize piling and foundation layouts. In the second stage, a detailed superstructure model is evaluated to check for excessive local vibration within the structure. The radiation damping (geometric damping) of soil-pile system mainly governs the vibration of foundation and structure. The stiffness and damping of foundation are frequency dependent, and generated. Then, impedances of the piled foundation are imported as boundary conditions to the FEM model.

2 SOIL-PILE-STRUCTURE INTERACTION

Many researchers have made contributions to the subject of soil-pile-structure interaction, such as (Dobry & Gazetas, 1988; Roesset et al, 1986; Gazetas & Makris, 1991; and Wolf; 1988). Recent alternative approaches were developed on this subject, such as analytical model based on homogenization methods by (Boutin & Soubestre, 2011). Macro-elements are used to model the soil-pile system by (Li et al, 2015). 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 separations often occur in the contact 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 nonlinear 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, 1967). Both theoretical and experimental studies have shown that the dynamic response of piles is very sensitive to the properties of the soil in the vicinity of the pile. Velestsos and Dotson proposed a scheme that can account for the mass of the boundary zone (1988). Some of the effects of the boundary zone mass were investigated by (Novak and Han, 1990), 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, 1995), not repeat 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 to practice to solve the problem for many projects. However, it should be explained that 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 the analytical solutions can be obtained for the impedance functions of a pile, and the software DYNAN (Ensoft, 2003) was developed based on the approach.

The group effect of piles is accounted for using the method of interaction factors. The static interaction factors are based on (Poulos and Davis, 1980). 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, 1982). There are six degrees of freedom for the rigid mat, and lateral vibration is coupled to rocking vibration. It should be explained that the foundations (or caps on piles) are assumed to be rigid. However, in most cases, the superstructures are flexible rather than rigid. The effects of soil-pile-structure interaction on dynamic response of machine foundations were discussed by (Han, 2008). The dynamic response of the superstructure can be calculated using FEM models by software SAP 2000 (Computers and Structures, 2007).

The radiation damping is the dominant energy dissipation mechanism in most dynamically loaded foundation systems, and also in the 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 a homogeneous isotropic medium. As a matter of fact, however, the soil is not a perfect linear elastic medium as assumed. It is well recognized in the soil dynamics field 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 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, 1992). The vibration measurements were done on group piles in the field to confirm the theoretical values modified for applications, see (Han and Yang, 2012).

The damping ratios were calculated based on the measurements from a dynamic test of steel pile in the field, as shown in Fig. 1 for horizontal vibration, and Fig. 2 for rocking vibration, see (Han and Novak, 1988). 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 $\theta =$ 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 up with the excitation intensities increased in this case.

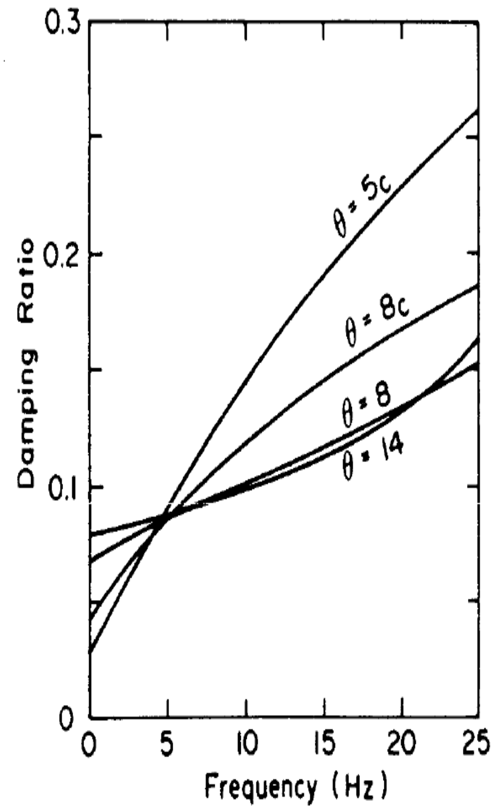

Figure 1 Horizontal damping ratio of pile

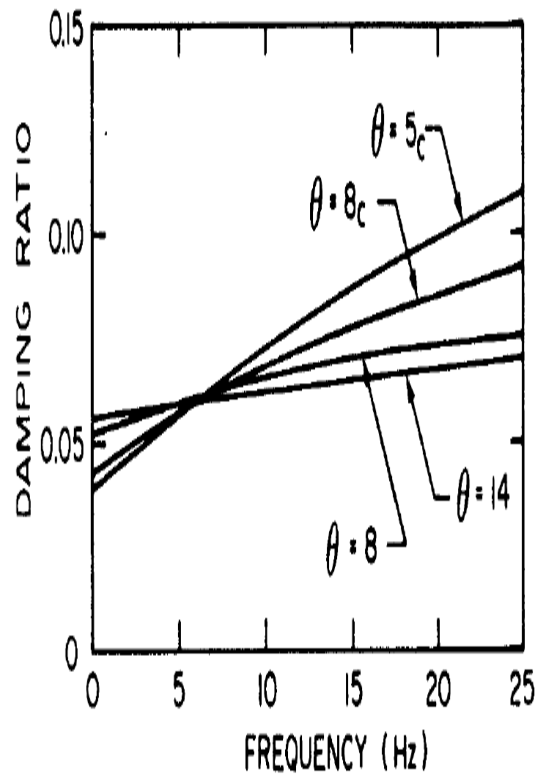

Figure 2 Rocking damping ratio of pile

3 SIMPLIFIED MODEL FOR DYNAMIC ANALYSIS

Execution of complex three dimensional dynamic analysis can be a complicated, 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 on FGP project 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 would be 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, complete 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 the 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 computational time, majority of the module superstructure has not been explicitly modeled as seen in Figure 3. Instead, 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 on dynamic response at module base where equipment is situated.

In order to validate the above assumption an analytical study has been undertaken to confirm the accuracy of analysis performed using this simplified model. Therefore, an additional model was developed to capture stiffness of the superstructure and to apply modal mass at module centre of gravity, thus providing a comparable alternative used in the validation exercise.

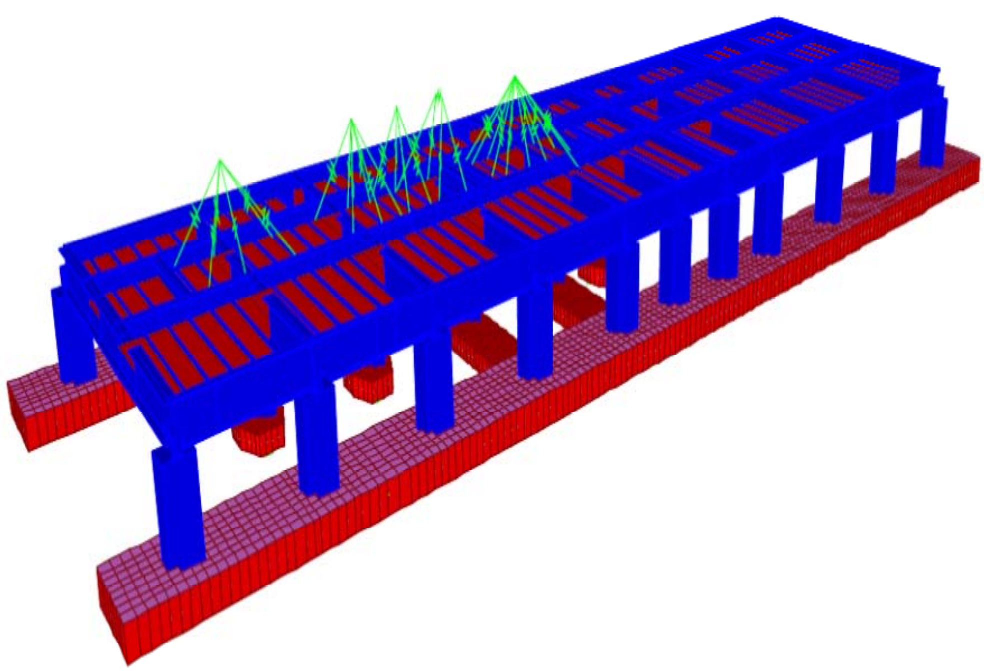

Figure 3: Model of foundation and mounted vibrating equipment for first stage analysis

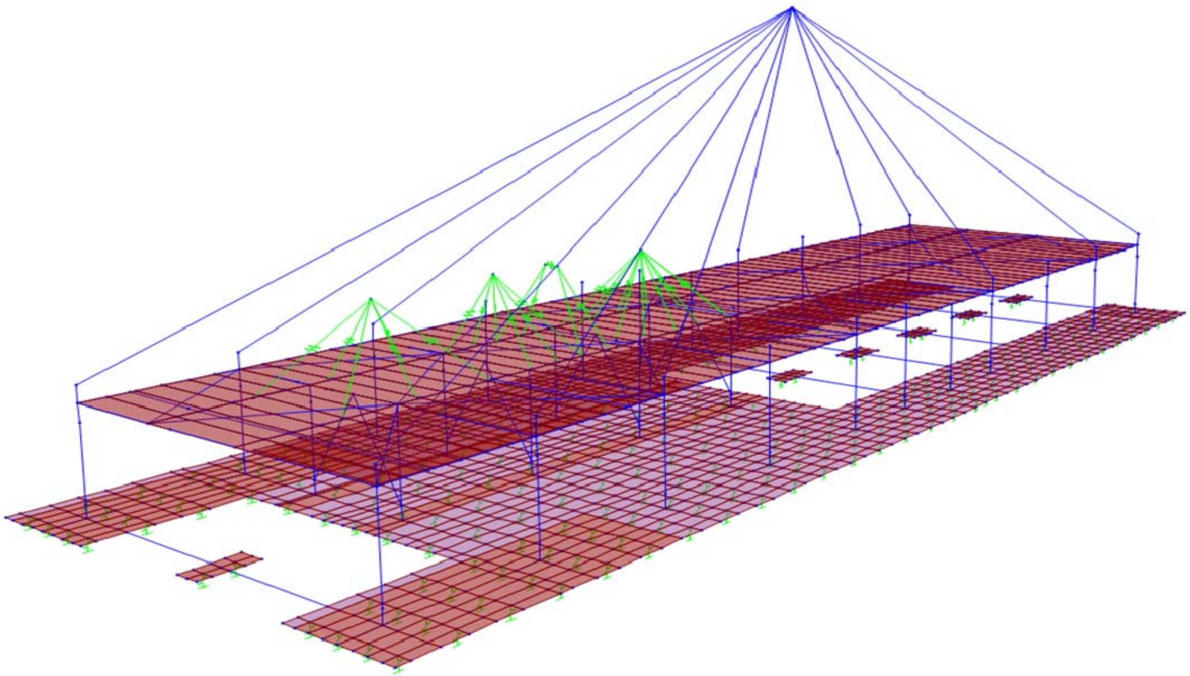

Figure 4: Effects for CG of steel frame located at the real elevation

To 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, 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 superstructure stiffness was then derived based on the relationship between loads and displacements obtained from static analysis.

Table 1: Comparison of dynamic response with different FEM 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

Obtained results enable several patterns to be identified. As anticipated, larger displacement amplitudes are achieved at lower operating frequency of the motor. This is partially contributed by the larger unbalanced force of the motor, but is also amplified by higher modal mass participation at lower operating frequencies. Varying of the boundary conditions has a minimal effect on the recorded displacement amplitudes. Lastly, no noticeable correlation in results can be observed between modal mass application approach and displacement amplitudes.

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 closed to that using the real model. In general, displacements obtained from the real structural 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 peak-to-peak amplitude displacements. 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.

In both analyses, over 99% of the modal mass participation is achieved within 80Hz frequency and notable variation in resonant modes is not observed for the range of analyses performed. Therefore, 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 accuracy or 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 FOR 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, supporting on pile foundation.

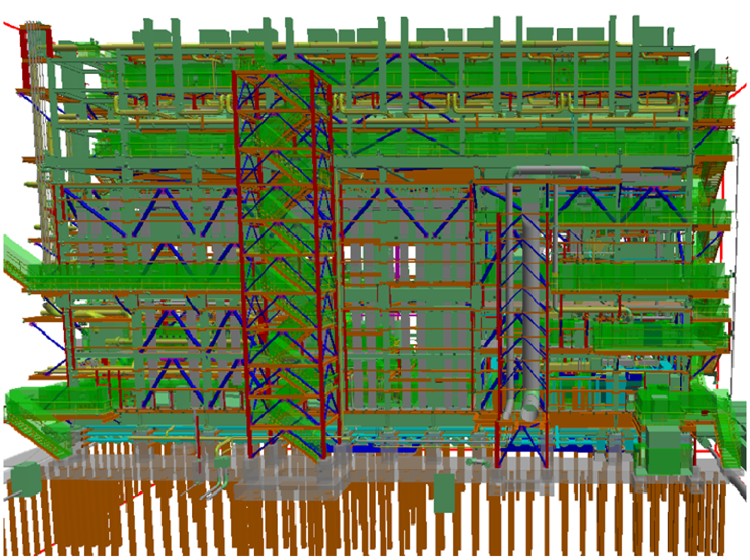

Figure 5 Module structure supported on pile foundation

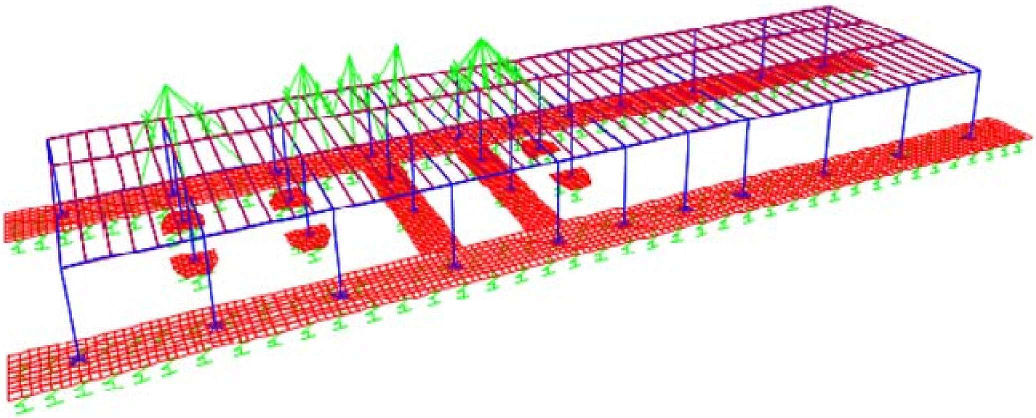

Figure 6 FEM model for Dynamic Analysis 1st Stage

The static design is done based on operating condition, road transport, sea transport and lifting to arrive at foundation layout and member sizes of the structural members in order to meet strength and deflection requirements. The half of pile capacity is allowable to be used under the vibrating equipment by some literature and document, to keep the behavior of soil-pile system in the linear elastic region. 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. The detail and qualified dynamic analysis have been carried out, and the vibration results obtained based on the reliable values of radiation damping. By judgement, the maximum load reached to 70% of pile capacity is accepted in this project.

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 for foundation part. In the early option, the spacing of pile is 1.2 m to keep the spacing to be three times of diameter, and total 312 piles. In another option the spacing is increased and total190 piles instead of 312 piles in preliminary stage. It is interested 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 on the project. The summary of final results for pile layout optimization is given in Table 2. The allowable vibration limit is 15.0 mm (peak-to-peak). It can be seen that the maximum amplitude of foundation with 190 piles meets the vibration limit. It is noted that during final geotechnical investigation to obtain reliable soil dynamic properties, two bore holes were considered under the module. Then average soil dynamic properties of two bore holes were calculated and used in pile Impedance calculation.

Table 2 Dynamic response of foundation with different pile number

Vibration Direction	Amplitude at Anchor Bolt Location (peak-to-peak, µm)					
	Pile layout – 312 piles			Pile layout- 190 piles		
	Motor (60 Hz)	Compressor (162 Hz)	TOTAL	Motor (60 Hz)	Comp (162 Hz)	TOTAL
Vertical	17.6	0.48	18.08	9.20	2.15	11.35
Lateral	10.60	0.70	11.30	13.90	0.27	14.17

From above dynamic analysis, it can be seen that the vibration of whole soil-pile-structure system is governed by the piled foundation. However, some excessive vibration may be caused by the local structure and arrangement, rather than the entire piles. For example, the vibration is reduced significantly in some location by added two small pile cap strips, as shown in Table 3. As shown in Figure 6 of first stage analysis FEM Model that local pile caps have been added at two grid lines. The area between those grid lines was very sensitive because this portion had loads from both compressor and motor and started vibrating in local modes with high vibration amplitude. The tie beams or pile cap strips helped to reduce the vibration a lot. In addition to introducing local pile cap strips, several other modifications were made as well. These modifications were changing the concrete pedestals to 1.0mx1.4m from 1.0mx1.2m (for exterior) and 1.2mx1.2m from 0.8mx0.8m (interior), intermediate steel posts to PIPE 450x25 from PIPE 250x10. The comparative results are presented in Table 3 before and after these modifications. The allowable vibration limit is 15.0 μm. It can be seen that the vertical amplitude is 37.94 μm, much higher than the limit. However, the maximum amplitude reduced significantly to be 14.17 μm, by added only two small local pile cap strips.

Table 3 Dynamic response of foundation with different pile cap

Vibration Direction	Amplitude at Anchor Bolt Location (peak-to-peak, μm)					
	Pile layout			Pile Layout with local pile cap strips		
	Motor (60 Hz)	Compressor (162 Hz)	TOTAL	Motor (60 Hz)	Comp (162 Hz)	TOTAL
Vertical	29.20	8.74	37.94	9.20	2.15	11.35
Lateral	13.70	0.20	13.90	13.90	0.27	14.17

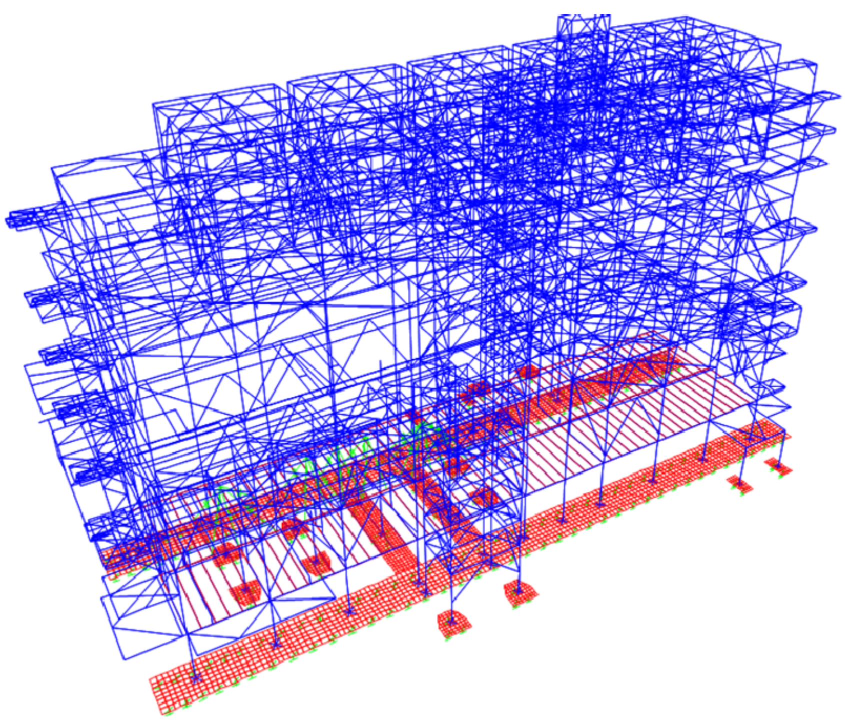

Figure **7** FEM model for Dynamic Analysis 2 nd Stage

Table 4 Comparison of dynamic response with different methods

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

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 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 4 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 calculated are close from the two methods. Too much vibration modes are involved for the complex superstructure, as 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 can be used for higher speed equipment.

5 CONCLUSIONS

The dynamic analysis is a complicated, time consuming and computationally demanding process for the modular structure, due to the complex superstructure, equipment and piping. It is better to divide into two stages. In the first stage the dynamic analysis is concentrated on the piled 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 closed to that from the real superstructure, and the results from the simplified model are reliable.

With the consideration of soil-pile-structure interaction, the piled foundation can be optimized. The cost of piles is saved and the dynamic response meets the allowable vibration limits. The radiation damping of foundation is the dominant energy dissipation mechanism, and the values of damping are justified based on dynamic tests in the software.

The vibration of whole soil-pile-structure system is governed by the foundation as shown in the first stage dynamic analysis. However, some excessive vibration may be caused by the local structure and arrangement, rather than the entire piles.

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