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Equipment-Structure Interaction and its effect on Seismic Demand

Jayarajan P
(Formerly Chief Engineer, Tecnimont India Private Limited, Mumbai, India. & Associate Professor, Dept. of Civil Engineering, MES College of Engineering, Kerala, India)

Abstract: *The seismic design and evaluation of structures built in petrochemical facilities present a challenging task for the design engineers. The structures found in these facilities can be broadly classified into building structures and nonbuilding structures. The"combination structures" wherein non-building structures such as vessels, exchangers etc. are supported by a steel or reinforced concrete primary structure represents a unique category in the perspective of seismic design. In reality, the seismic behavior of combination structures is mainly governed by the complex interaction between the primary structure and nonbuilding structures. A good understanding of equipment structure interaction is essential in the design of both the nonbuilding structure as well as the primary structure. The paperpresents the results of a seismic assessment study performed on a multistoried steel primary structure supporting a vertical vessel representing a combination structure. Both thecoupled and decoupled models were analyzed for two weight ratios representing the weight of nonbuilding structure in terms of effective seismic weight of the system. The analysis results highlight the importance ofweight ratio in the structure-equipment interaction affecting their assessment and design.*

Keywords: *Equipment structure interaction,Combination structure,Coupled model,Seismic demand,Linear dynamic time history,Nonbuilding structure, Petrochemical facilities.*

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I. Introduction

The structures found in petrochemical facilities can be broadly classified into building and nonbuilding structures. The building structures normally include typical single-storied buildings such as administration buldings, substation and control room buildings. The nonbuilding structures can be either similar to buildings such as pipeways & equipment support frames or not similar to buildings as in self- supporting equipment items.The nonbuilding structures can also be supported on primary building structures and comes under the category of *combination structures*. The performance of combination structures is greatly influenced by the equipment-structure interaction (ESI) and accordingly the design engineers of such structures need to be more cautious in applying design code regulations which are primarily developed for building structures. Typical examples of combination structures are shown in Figure 1.

In petrochemical plants, the foundations and the supporting structures are to be first built as per the project schedule later followed by equipment erections. In many cases, the design engineers are provided with highly conservative load data by equipment vendors during foundation designs which are later refined during supporting structure calculations. Theconventional design approach followed by the structural engineer is to lump the weight of equipments at locations &elevations provided by equipment vendors irrespective of their weight and dynamic characteristics. The equipment vendors on the other hand completes the design check for their equipments and vessels based on project specific documents. This practice is despite the coupling and decoupling criteria specified for equipment-structure interaction analysis in many international codes of practice. The approach ultimately results in very conservative but uneconomical designs for both the structure and equipments. It is important that structural engineers and equipment vendors maintain a close collaboration in listing critical equipment items that are likely to influence both the structural and equipment behavior. In such cases, an equipment-structural interaction analysis shall be undertaken and the conclusions obtained reviewed before arriving into an economic design.

A literature survey indicates that only limited case studies are available covering equipment structure interaction with majority falling into nuclear plants. Azizpour O. and Hosseini M. [1] studied the interaction between piping and the supporting pipeways to investigate the seismic behavior of entire system. It was concluded that in addition to the percentage of piping weight, both the piping end conditions and their connection to the pipeways can significantly affect the seismic behavior. Prabhakar G. et al. [2] reviewed the decoupling criteria with respect to structural response of nuclear power plant structure. The structural response of calandria vaultsupporting the calandria endshield assembly (CEA) of pressurized heavy water reactor was studied using both the coupled and decoupled models.The mass of structure above the CEA was found to play a major role in altering the structural response.Subramanian KV et al. [3] studied the effect of coupled analysis relevant to nuclear safety systems and concluded that the decoupling criteria stipulated in the codes and standards would result in economical design of both the primary and secondary systems. M.Perez, Y et al. [4] performed an assessment of the advantage of coupled modelling over the decoupled system using the secondary system represented by equipments of increasing weight while keeping the primary system unchanged. It was confirmed that consideration of coupling leads to a reduced horizontal response with increase in the weight of equipments.

The document “Guidelines for seismic evaluation and design of petrochemical facilities” [5] provide detailed guidelines in the seismic design of new petrochemical facilities and the seismic evaluation of existing facilities. The intent of the document is to help design engineers working in the detailed engineering of industrial plants in correctly interpreting the codal provisions and to provide practical guidance and design details. Appendix 4.B of the publication provide guidelines for determination of base shear for combination structures.

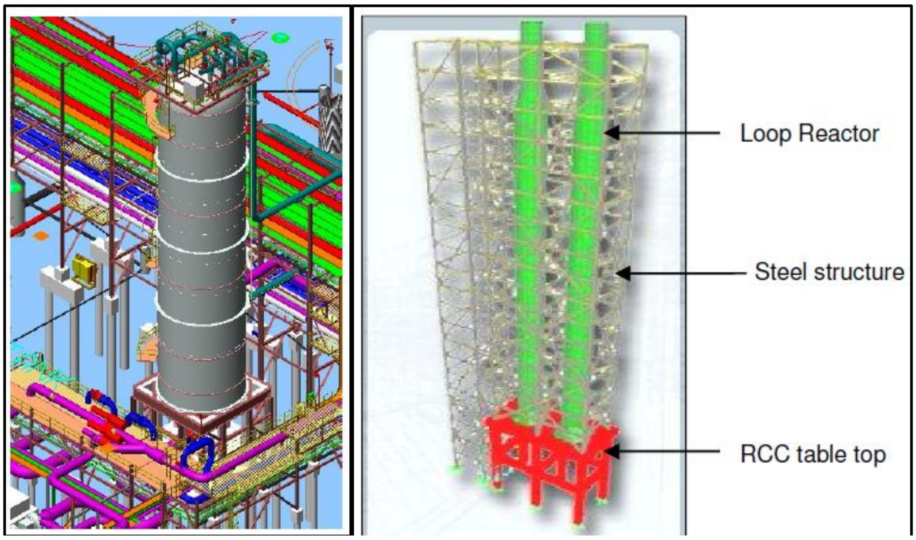

Figure 1 Examples for “Combination structures” in petrochemical facilities

II. De-coupling Criteria for Combination Structures

Various international codes of practice specify their de-coupling criteria to assist the design engineers in choosing a proper method of analysis for combination structures. Based on these criteria, engineers can take crucial decisions regarding whether the supported nonbuilding structure shall be designed either as a non-structural component or as part of primary structure.The de-coupling criteria used in the present study are based on ASCE standard ASCE/SEI 7-16[6]. The standard provides three scenarios to enable the choice of proper analysis and design methods. The scenarios are presented in Figure 2.

Case-1 represents the condition where the weight of the nonbuilding structure(NBS) is less than 25% of the combined effective seismic weights of the NBS and the supporting structure(SS), the design seismic force for the NBS calculated considering it as a nonstructural component. The supporting structure shall be designed treating it as a building structure with the mass of NBS lumped at appropriate location. In cases, where the weight of NBS is higher than 25% of combined seismic weights of NBS and SS(represented by cases 2&3), the analysis procedure shall be decided based on the fundamental period(T) of NBS. Where T is less than 0.06 s (case-2), the NBS shall be considered as a rigid element with appropriate distribution of its seismic weight. The design considerations for NBS & SS remains same as in case-1. In cases, where T is greater than or equal to 0.06 s (case-3), the NBS and SS shall be modelled together in a combined model. The behavior factor (R) in this case shall be taken as the lesser R value of NBS or SS. The NBS & SS shall be designed based on the forces obtained from combined analysis.

Based on the above decoupling criteria, the present study on equipment structure interaction(ESI)essentially focusses on two scenarios. In the first one, the weight of NBS is kept much larger than the code specified limit of 25% and the effect of ESI on the seismic demands of SS and NBS investigated. In the second scenario, the weight of NBS is kept less than 25% and the effect of ESI investigated. In both cases the fundamental period of the NBS is kept more than 0.06 s.

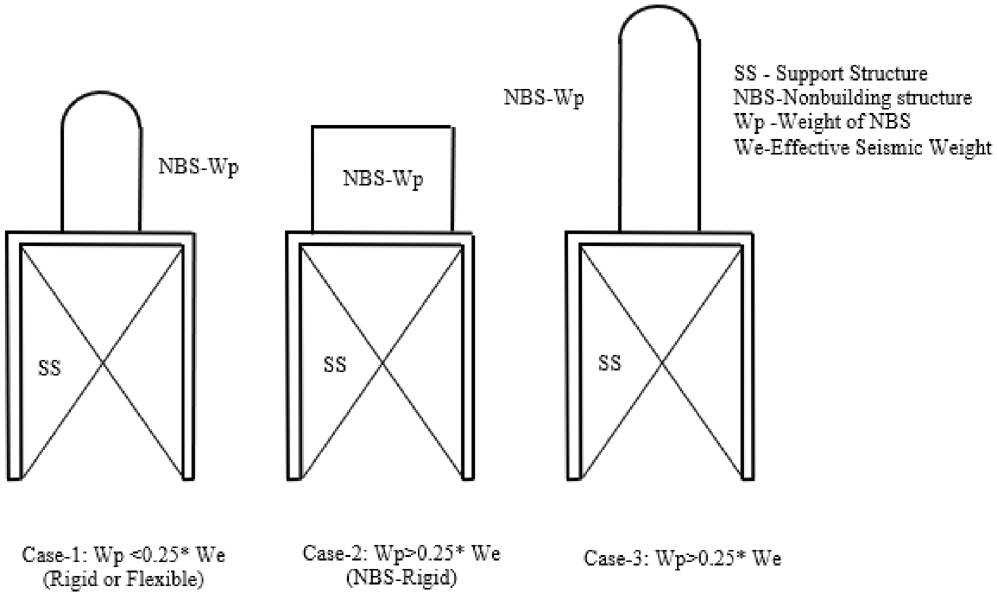

Figure 2 Categories of"Combination structures" [ASCE-7]

III. Modelling and Equipment Structure Interaction Analysis

The building model used in the present study is a typical of petrochemical facilities. The model is a three storied framed steel structure employing ordinary moment resistant frames (OMRF) in one direction and ordinary concentrically braced frames (OCBF) in the other direction. The structure has plan dimensions of 6x6m and a storeyheight of 4.0m. The corrugated reinforced cement concrete(RCC) floor slab is supported over secondary beams. The equipment considered for the study is of 12m height and 2.5m diametersupported over the top floor. Equipment weights of 500 kN and 125 kN are considered representing 48.5% and 19.5 % of effective seismic weight. In each case two types of analysis are performed, the first considering the SS& NBS as separate models representing a de-coupled analysis and the second representing a coupled analysis with combined modelling of NBS and SS. The corresponding structural models are shown in Figure 3. In all analysis cases, the SS and NBS are kept the same for easy comparison. The soil structure interaction is not considered in the present study. The computation of elastic seismic demand in each case are done through dynamic linear time history analysis using the finite element software SAP2000[7].In decoupled analysis, the mass representing the eqpt is lumped at its supporting location in the SS without considering the stiffness. The acceleration time history records obtained from SS analysis at the supporting location is then used as the input loading to calculate the response of NBS.

The ground motion (Record Station No. RSN-79) was selected from PEER(Pacific Earthquake Engineering Research Center) database [*https://peer.berkeley.edu/peer-strong-ground-motion-databases*]and scaled to match the horizontal elastic response spectrum of Eurocode 8 [8] for the considered soil type and peak ground acceleration.The elastic spectra,scaled ground motion response spectra and the time history of earthquake motion used for the study are presented in Figure 4. The same ground motion was appliedseparately in X & Y directions for both models.

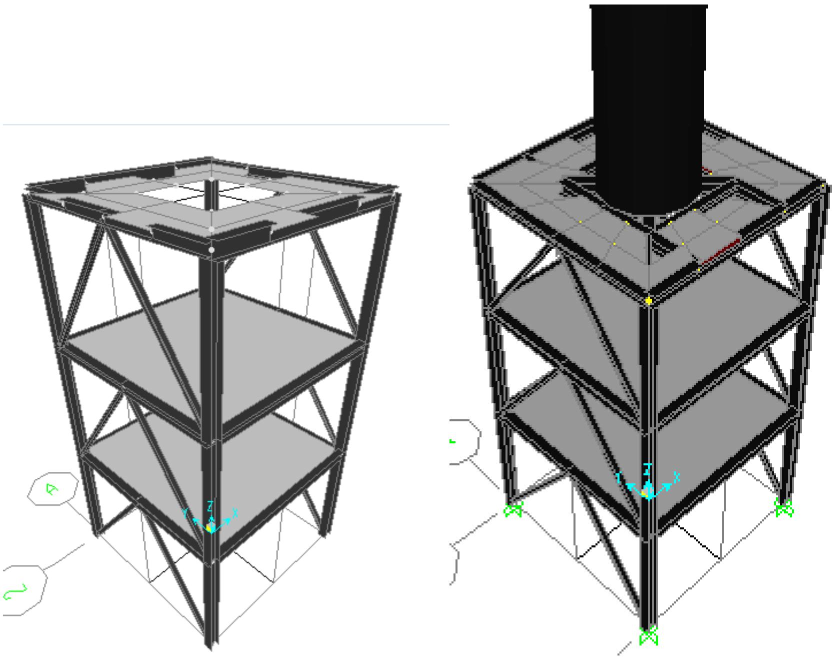

Figure 3 Decoupled and coupled structural models
(only limited portion of equipment. shown for clarity)

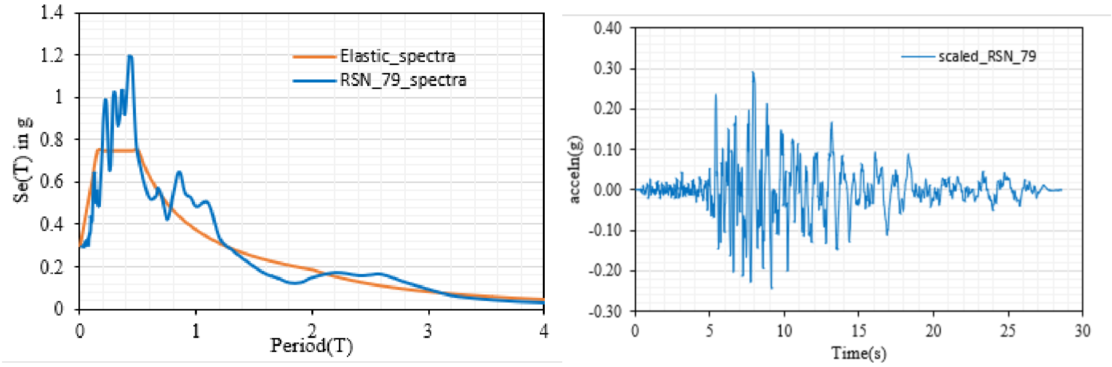

Figure 4 Ground motion characteristics (a) response spectrum (b)time history of scaled ground motion

3.1. Equipment-structure interaction: Weight of equipment more than 25% of effective seismic weight

To study the effect of equipment-structure interaction, the equipment weight is first set to 48.5 % of the effective seismic weight far above the code-specified limit of 25%. The predominant period for the equipment obtained by the modal analysis is 0.116 s (ie.8.62 Hz), above the code specified value of 0.06 sec. The selected parameters require that a coupled analysis be performed to obtain the design forces for both the SS and NBS.Therefore, a coupled analysis is first performed followed by a decoupled analysis to study the effect of interaction. The elastic seismic base shearscalculated for supporting structure and the equipmentare taken as a parameter for interpretation of results.

The elastic seismic base shears obtained for the structure considering both coupled and decoupled analysis is presented in Figure 5.The structural systems are different in X and Y directions and therefore the results are given for both directions It shall be noted that in each case the design base shear shall be obtained by dividing the elastic base shear by the behavior factor (R) representing the structural system. It is observed that the coupled modelling lengthens the period of the structure and invoke the participation of higher modes. The base shear for SS is thus governed by the frequency content of ground motion, modal characteristics of the structure and the stiffness& mass distribution of the supported equipment. It is found that the structure base shear in X direction calculated for the coupled model is only 44.3 % of decoupled model. However, in Y-directionthe results for the structure are almost the same in both models.

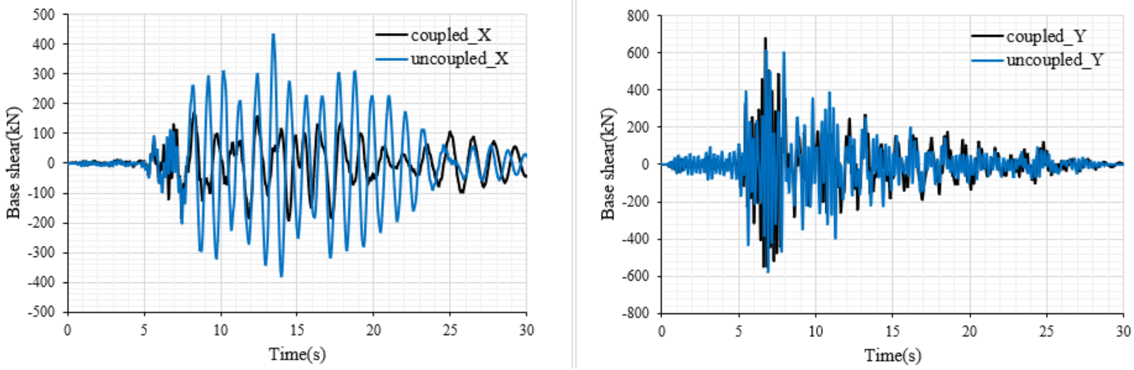

Figure 5 comparison of elastic base shears for the SS considering both models(clause 3.1)

The seismic base shear demand for the equipment in coupled analysis was calculated directly from the coupled model subjected to the ground motion.However, in the case of decoupled model, the acceleration time history corresponding to the equipment supportlocation obtained from the structural model provides the input load for the equipment. The response spectra for support acceleration in the X- and Y-direction is shown in figure 6. The seismic base shear demand calculated for the equipment for both the models is presented in figure 7.It is observed that seismic demand for the equipment computed for the coupled model is only around 30% of decoupled model in both directions. The summary of results is presented in Table1.

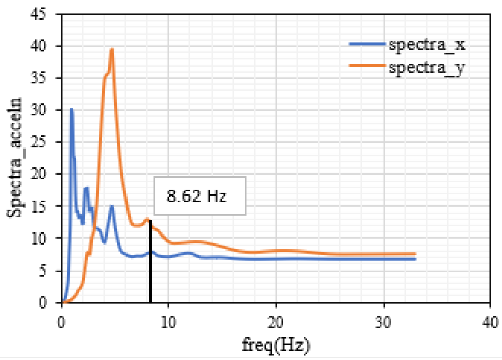

Figure 6 Response spectra for the equipment support from decoupled structure model(clause 3.1)

3.2. Equipment-structure interaction: Weight of equipment less 25% of effective seismic weight

The equipment weight is next set to 19.5 % of the effective seismic weight below the code-specified limit of 25%. The predominant period obtained for the equipmentin this case is 0.061 s (ie.16.4 Hz). The selected parameters require that anuncoupled analysis is sufficient to obtain the seismic demands for both the structure and equipment. However, a coupled analysis followed by a decoupled analysis is performed in this case as well to understand the extent of interaction. Similar to the earlier case, the seismic demands for both the structure and equipment are evaluated for both the coupled and decoupled models. The relevant results are presented in figures 8-10.It is found that in X-direction the seismic demands for the structure are almost the same in both models. However, the seismic demand computed in Y direction for the coupled model is only 66.3 % of decoupled model,indicating a lesser scale of interaction compared to the earlier case. Regarding the equipment, the seismic demand for coupled model is on an average 75% of corresponding values for decoupled model again indicating lesser degree of interaction for a lower weight ratio. Table 1 presents the summary of results.

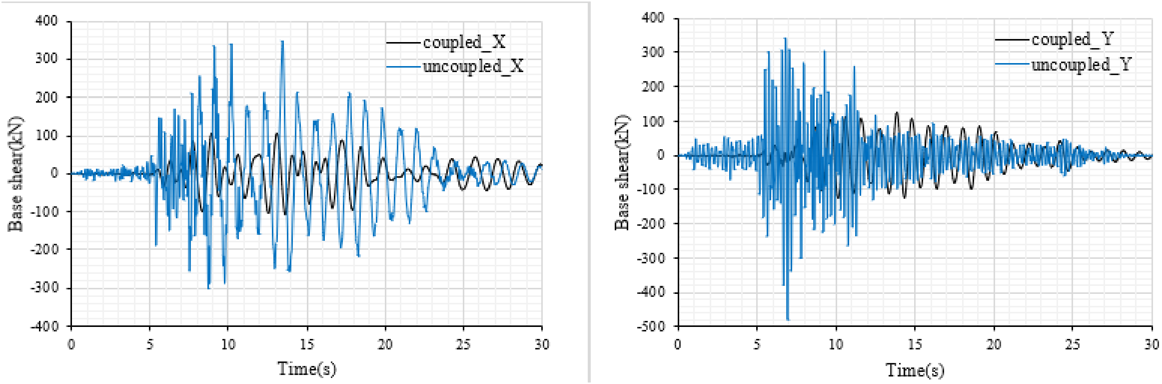

Figure 7 comparison of elastic base shears for the eqpt. considering both models (clause 3.1)

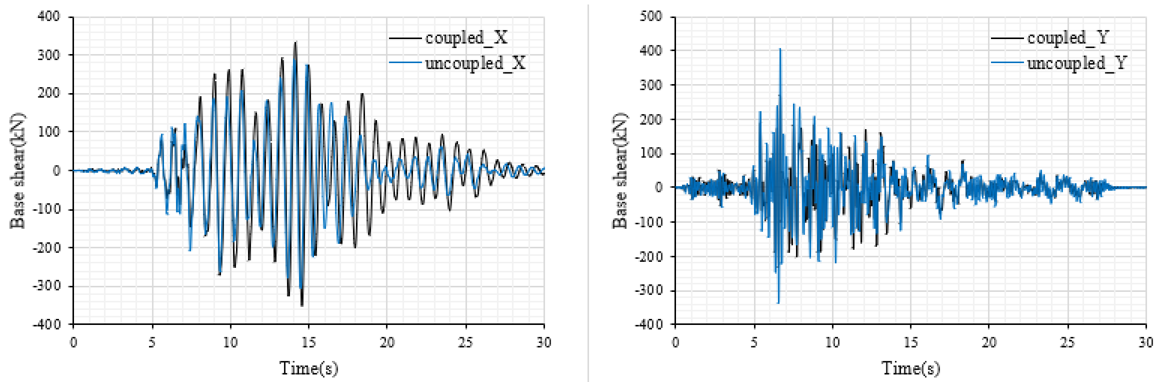

Figure 8 comparison of elastic base shear for SS considering both models(clause 3.2)

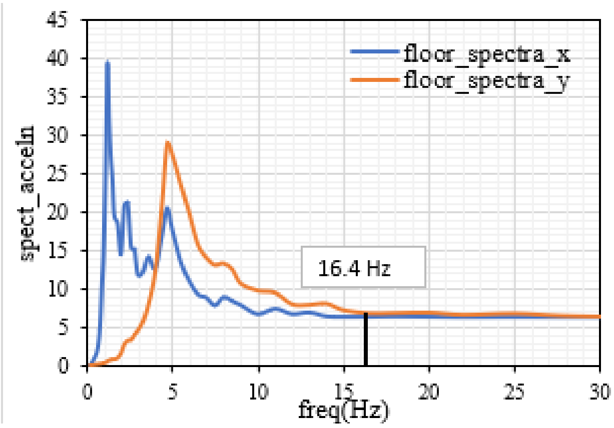

Figure 9 Response spectra for the equipment support from decoupled structure model(clause 3.2)

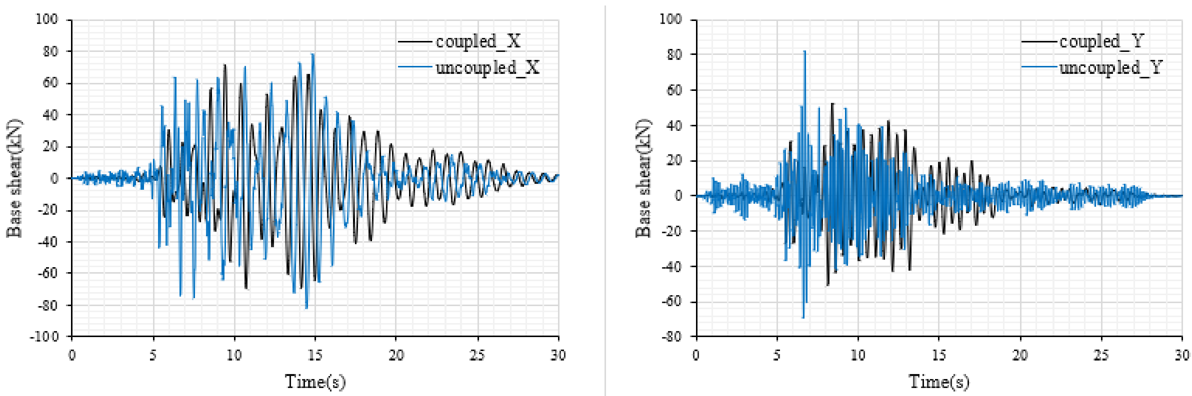

Figure 10 comparison of elastic base shear for the eqpt. considering both models (clause 3.2)

Table. 1 Summary of results

Description	Case-1: Wp>0.25*effective seismic weight (ratio=0.485)		Case-2: Wp<0.25*effective seismic weight (ratio=0.195)	
	Coupled	Decoupled	Coupled	Decoupled
Structure				
Seismic demand-Vx(kN)	192	434	350	302
Seismic demand-Vy(kN)	678	612	268	404
Equipment				
Seismic demand-Vx(kN)	106	348	71	82
Seismic demand-Vy(kN)	128	478	52	82

IV. Conclusions

In the present study, a “combination structure” typical of petrochemical facilities consisting of a conventional steel structure supporting a nonbuilding structure (NBS) was analyzed considering boththe coupled and decoupled models. The weight ratios(ratio of weight of NBS to effective seismic weight of the system) of 0.485 and 0.195 were selected to investigate the effect of weight of NBS on equipment-structure interaction (ESI). These values were chosen based on the decoupling criteria limit of 0.25 asstipulated in ASCE-7.The NBS in each was flexible as concluded from its modal analysis. The analytical investigation emphasizes the importance of weight ratio on the overall ESI. The model with a large value of weight ratio shows significant ESI effects identified by larger reductions in base shear demand for both the structure and NBS. The ESI effects were seen even in models with lower weight ratio though limited. While a reduction in the seismic demand was observed in NBS, the beneficial effect on the supporting structure is essentially governed by the extent of period lengthening and the influence of higher modes.

The investigation underlines the importance of a collaboration between structural engineers and equipment vendors for critical items identified by larger weight ratio. The objective of such a collaboration would be to achieve a safe and economical design for both the supporting structure and the NBS. Special attention and discussions with equipment vendors would be required for structures subjected to nonlinear analysis. This is particularly due to the recommendation of a lower value of behavior factor (R) by ASCE for systems with weight ratio larger than 0.25.

Acknowledgement

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