Seismic Assessment of Pipe Rack Considering Coupled and Decoupled Case

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Abstract

Pipe racks are important part of Industrial Structures such as oil refineries, petrochemical sector, as they are used to support piping systems that transports fluids from one place to the other. The aim of this study is to carry out Linear Dynamic Analysis of Ethanol gas plant pipe rack considering coupled and decoupled case (for both pipe empty and operating conditions), using ANSYS and validating with Staad Pro. While analyzing pipe rack generally, the point masses calculated due to the weight of piping system and fluid are applied on the pipe rack structure, which usually satisfies the seismic mass criteria, but the stiffness added due to piping system and their supports are been neglected. The effect on seismic demand of Pipe rack, due to additional masses and stiffness of piping system have been checked. It is observed that in coupled case the modal frequencies of the structure is higher due to additional pipe stiffness, but at the same time base shear values are lower as compared to decoupled case, which can further direct towards the change in response reduction factor (R) for both the cases which may eventually result in reduced base shear values.

Keywords
Pipe rack, piping system, Linear Dynamic analysis, coupled and decoupled case and response reduction factor.

1. Introduction
The pipe rack is typically constructed from frames in steel or concrete and the pipeline assembles on top of it. Such pipe rack systems should be critically designed for seismic forces, as failure of non-structural components may cause damage to the nearby units. The accidents in chemical plants are recurrent and occur frequently exposing human lives and environment at danger (Sarno and Karagiannakis 2020). IS code 1893-part 4 2015 deals with these type of Industrial Structures and, recommends to carry modal analysis with all the stiffness of lateral as well as vertical load resisting members and masses of the structure modelled for calculating natural time period and linear dynamic analysis for analysis and design purpose. Equipment structure interaction is required to be considered for flexibly mounted equipment if ratio of masses of secondary structure (piping system or equipment) and primary structure (steel or RCC frame) exceeds 0.25. In this study 2 different cases are considered, case I where pipe rack are only modelled and load of piping system is applied in form of point loads (decoupled case for both empty and operating loading conditions) and case II where both pipe and pipelines are modelled considering the supporting conditions. Pushover analysis is carried out in Staad Pro in order to calculate response reduction factors for both the cases.

1.1 Objectives
- To Perform Time History Analysis of pipe rack on ANSYS and validation of results using Staad-Pro.
- Comparative study of seismic response for coupled and decoupled case.
- Evaluating Response reduction factor for both Coupled and Decoupled case.

2. Literature Review

A Review of different literatures is done here to collect available information and summarize the knowledge in the field of petrochemical, oil and gas sector (Industrial structures-pipe rack system).The purpose of this is to understand the different codal provisions, various analysis methods used for seismic assessment of pipe rack and results and discussions available for the same. As Analysis and design of such industrial structures is of crucial importance, and implementation and interpretation of codal provisions becomes essential.

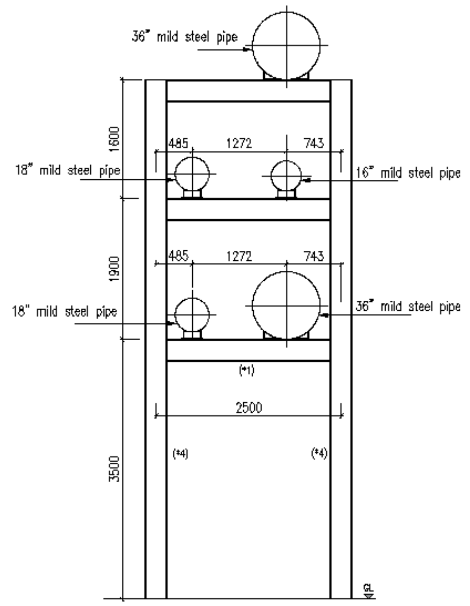
Sarno and Karagiannakis (2020) carried out critical seismic assessment of steel pipe rack, and also compared different codal provisions namely behavior factors, importance factors and acceleration response spectra. In the present study a three floor petrochemical pipe, which is 12m high, 4m each floor, it consists of a piping system that runs along the length and height of third floor, piping system transfers a hazardous but nontoxic material namely Propylene, modelling of the system was carried out in ABAQUS. In present study both non-structural components and support structure are modelled and analyzed together since wp >25% and T >0.06 for estimating fundamental frequency. Current study they have used Pushover analysis for estimating behavior factor and then followed by incremental Dynamic analysis to compare the results.

Farhan and Bousias (2020) analysis of a LNG sub-plant was carried out considering component dynamic interaction. A RCC pipe rack and pipelines both were analyzed in linear regime considering both coupled and decoupled case in ABAQUS. Drift demand due to coupled case is observed to be reduced due to presence of pipelines and their supports. Along with this fragility analysis was carried out in order to examine the vulnerability of the structure considering both the cases, which further helped to conclude that for pipes and columns the vulnerability decreases in coupled case, but for the RC beam of the rack it shows higher vulnerability due to the loadings exerted on them from pipelines at support end.

Puttat (2019) stated that seismic analysis of a petrochemical facility, with heavy equipment supported at the top floor. Here two different weights of the equipment have been considered in order to match the weight ratios confirming both equipment weight exceeding 25% of the structure weight and equipment weight less than 25% of structure weight given in ASCE/SEI 7-16 for equipment structure interaction, along with this coupled and decoupled cases for both the above considerations were carried out. Author in this paper concludes that model with higher weight ratio value shows identifiable effects due to equipment structure interaction resulting in larger reduction in base shear values of both structure and equipment.

3. Case study

The Case Study considered in this research paper repeats an existing Ethanol Gas Pipe rack, with total height of 7.00 m above GL. The plan and section view of pipe rack is illustrated in Figure 1 and 2. It is 3 tier steel framed pipe rack, width of the pipe rack is 2.5 m and the length is 30m, with 5 bays of 6m each. Pipelines with different diameters are supported on pipe rack. Linear time history analysis is carried out in order to compute the seismic responses (Figure 1 and Figure 2).



(1*) – ISMB 350
(2*) – ISMB 300
(3*) – ISMB 200
(4*) – ISHB 350
(5*) – ISA 90*90*10

Figure 1. Section view of pipe rack

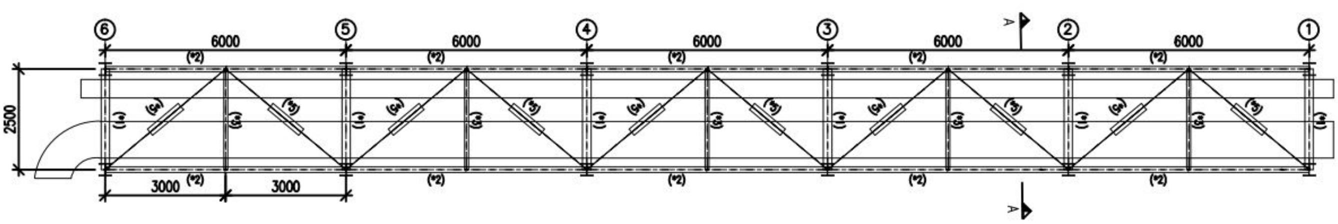


Figure 2. Plan view of pipe rack

4. Methodology

The methodology is an appropriate outline for research, an understandable scheme based on study, principles, and values that guides the choices researchers make. Considering the parallel approach, I choose the following methodology for the completion of my research work (Figure 3).

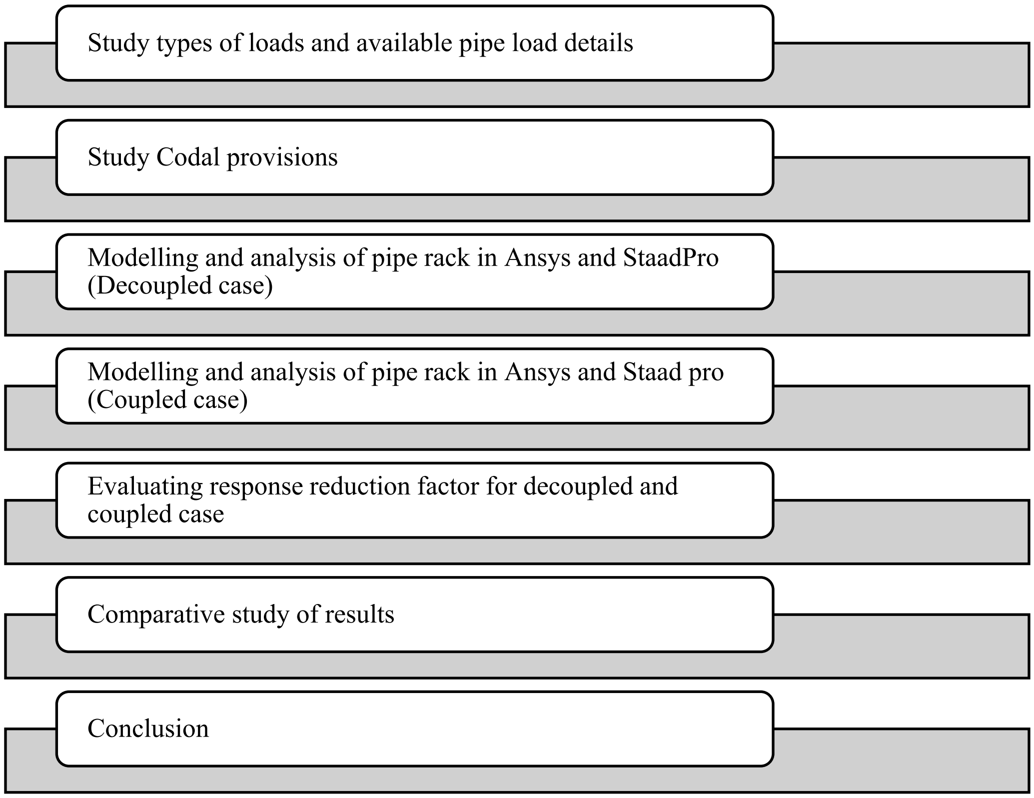


Figure 3. Steps in methodology

4.1 Type of loads and Pipe load details

4.1.1 Type of loads considered

Pipe empty load (PEL) - It is empty weight of pipelines including weight of venturi meter, valves etc.
Pipe operating load (POL) - It is empty weight of pipelines including weight of venturi meter, valves etc, and along with the weight of fluid carried by the pipes. Guide/ Anchor Load - Loads on pipe rack beam due to vertical and transverse restraints applied to pipelines. Thermal Load/ Axial Restraints – Load due to thermal effect resulting in frictions forces in longitudinal direction (Figure 4 (a) and (b).

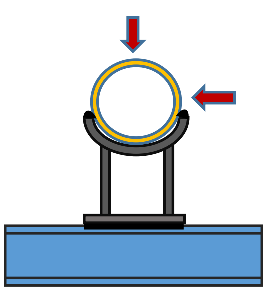


Figure 4 (a) Anchor/Guide Load

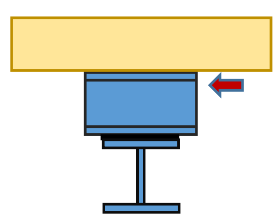


Figure 4 (b) Load due to axial restraints

4.1.2 Pipe Load details

Pipe lines are supported on vertical rigid support whose reactions are then imposed on pipe racks for analysis. The loading details for this case study composing of imposed loads on pipe due to vertical and horizontal reaction of vertical rigid supports, supporting pipe lines are illustrated in table 1.

Table 1. Pipe Load details

Elevation (m)	Grid No	Pipe Diameter (inches)	Load(KN)			
			Pipe Empty condition	Pipe Operating condition	Guide Load	Axial Restraint (Thermal)
3.50	1	36	111	128		
	2	36	111	128	23	
	3	36	33	36		
	4	36	26	26	11	8
	5	36	77	88		
	6	36	77	88	12	
3.50	1	18	11	19		
	2	18	9	9	12	
	3	18	11	12		40
	4	18	9	21	3	
	5	18	11	17	5	
	6	18	16	17		
5.40	1	18	17	19		
	2	18	17	19	17	17
	3	18	17	19		
	4	18	17	19		
	5	18	12	31	17	
	6	18	17	19		
5.40	3	16	17	17	6	
	4	16	17	17	9	13
	5	16	5	38	34	
	6	16	9	11		
7.00	1	36	115	160		
	2	36	115	160	18	
	3	36	35	79		
	4	36	23	25	10	16
	5	36	19	24		
	6	36	49	89	45	

4.2 Codal provision

4.2.1 Structure categorization

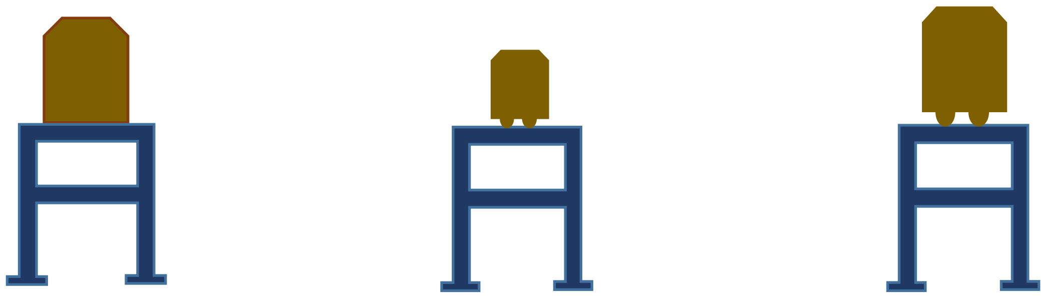
As it is an ethanol gas plant pipe rack structure, ethanol being highly flammable any damage to the piping system may be potentially dangerous from safety point of view, hence the structure is categorized as category 2, confirming IS 1893 part 4, clause 8.1.

4.2.2 Equipment Structure interaction

According to IS 1893 Part 4, interaction between the isolators (Flexible mount for support of equipment) and the structure shall be measured by suitably modeling the isolators support system while considering the equipment as lumped mass (coupled analysis) if the following condition is satisfied

$$\frac{M_F}{M_S + M_R} = \frac{1321 \text{ kN}}{201 \text{ kN}} = 6.5 > 0.25$$

M_S = total mass of the primary system (structural system) on which the secondary system is supported, M_R = total mass of all the equipment that are rigidly mounted at different locations in the structure, and M_F = total mass of all the equipment that are flexible mounted (on isolators) at different locations in the structure. Figure 5 recaps criteria for equipment structure interaction as per IS 1893 Part 4 (2015) (Figure 5).



Equipment rigidly connected to structure

Flexible connection with $\frac{M_F}{M_S+M_R} < 0.25$

Flexible connection with $\frac{M_F}{M_S+M_R} > 0.25$

Figure 5. Equipment Structure Interaction Criteria according to IS-1893-PART 4 (Pisal et al. 2018)

4.3 Modelling and Analysis Decoupled case

In this case only the pipe rack is modelled in ANSYS and Staad Pro. While modelling in ANSYS columns and beams were modelled as 1D beam element and horizontal and vertical bracings were modelled as link/truss elements. Similarly in Staad Pro 1D line elements with beam and truss specifications for beam, column and bracings were modelled respectively. The frame in lateral direction is considered to be moment resisting frame, while in longitudinal direction is considered as concentric braced frame, these conditions are achieved by giving appropriate releases to the model. Physical properties of the steel members is taken unit mass of steel, p = 7850 kg/m~ Modulus of elasticity, E = 2.0 x 10s N/mm2 (MPa) Poisson ratio, p = 0.3 Modulus of rigidity, G = 0.769 x 10s N/mm2 (MPa) Co-efficient of thermal expansion cx. = 12 x 10' /"c, confirming IS 800-2007 clause 2.2.4.1. Figure 6 (a) and (b) shows pipe rack modelled considering decoupled case.

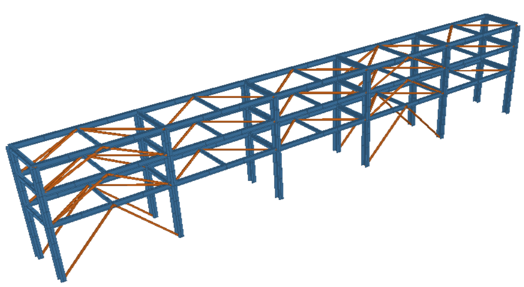


Figure 6 (a) Pipe rack in Staad Pro (decoupled case)

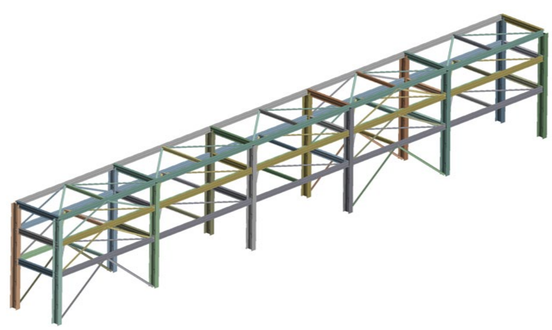


Figure 6 (b) Pipe rack in ANSYS (decoupled case).

Dynamic linear analysis using Bhuj time histories is performed in both the software considering pipe empty and pipe operating conditions, modal responses, drift and base shear results are extracted for both the conditions. Figure 7 shows ground acceleration vs time graph for bhuj time history.

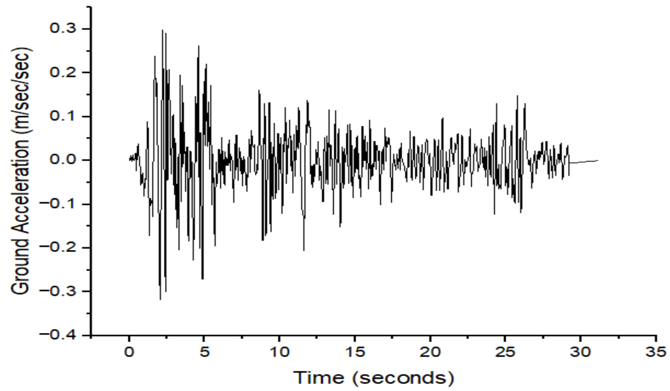


Figure 7 Bhuj Time history

4.3 Modelling and Analysis Coupled case

In this case both pipe lines and pipe rack were modelled together in ANSYS and Staad Pro. While modelling in ANSYS pipelines of 36" diameter were connected to beam with rigid link using remote points, whereas for pipelines with diameter 16"and 18" were supported on vertical members with cross sectional properties approximately similar to that of shoe support with saddle. Pipe constraints were provided by using remote displacement command at the top node of the vertical member supporting pipe, the bottom part of vertical members is rigidly connected to the beam of pipe rack. In Staad Pro by using offset command a rigid link between pipe line (36") and pipe rack is created, which showcases the vertical rigid supports used for resting pipelines and for other diameter pipes (16" and 18") vertical supports are modelled. Appropriate constraints are provided to the pipeline depending up on their boundary conditions. While applying constraints to the pipeline of 36" diameter which is directly resting on beam, reduced stiffness value according to the guide load requirement in that direction is applied. The below given table illustrates the pipe constraints used while modelling (Table 2).

Table 2. Pipe constraints

Elevation	Grid No	Pipe Diameter	UX	UY	UZ
3.500 m	1	36"	Free	Free	Free
	2	36"	Free	Restrained	Restrained
	3	36"	Free	Free	Free
	4	36"	Restrained	Restrained	Restrained
	5	36"	Free	Free	Free
	6	36"	Free	Restrained	Restrained
3.500 m	1	18"	Free	Free	Free
	2	18"	Free	Restrained	Restrained
	3	18"	Restrained	Free	Free
	4	18"	Free	Restrained	Restrained
	5	18"	Free	Restrained	Restrained
	6	18"	Free	Free	Free
5.400 m	1	18"	Free	Free	Free
	2	18"	Free	Restrained	Restrained
	3	18"	Free	Free	Free
	4	18"	Free	Free	Free
	5	18"	Restrained	Restrained	Restrained
	6	18"	Free	Free	Free
5.400 m	1	-	-	-	-
	2	-	-	-	-

	3	16"	Free	Restrained	Restrained
	4	16"	Restrained	Restrained	Restrained
	5	16"	Free	Restrained	Restrained
	6	16"	Free	Free	Free
7.000 m	1	36"	Free	Free	Free
	2	36"	Free	Restrained	Restrained
	3	36"	Free	Free	Free
	4	36"	Restrained	Restrained	Restrained
	5	36"	Free	Free	Free
	6	36"	Free	Restrained	Restrained

Additional masses due to weight of fluid and other equipment are added in form of distributed mass on pipe lines. While modelling in ANSYS and Staad Pro 1D pipe element were used to model pipe lines. Pipe idealization command was used for elbow elements (Figure 8).

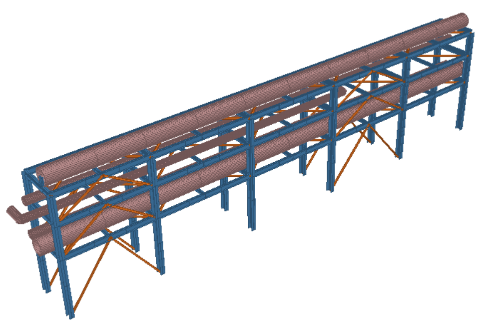


Figure 8 (a) Pipe Rack with Pipe Model in Staad-Pro.

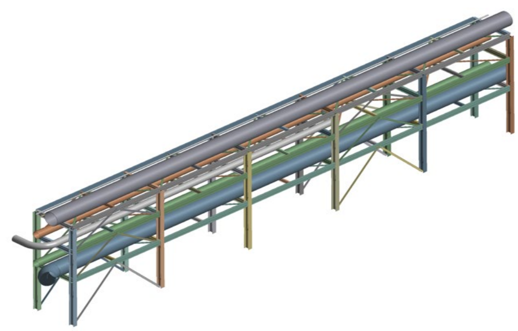


Figure 8 (b) Pipe Rack with pipe Model in ANSYS.

5. Response Reduction Factor

While carrying out Coupled analysis it is difficult to predict the behavior and seismic response of the structure due to pipe and pipe rack interaction, hence it becomes necessary to assess reliability of results for coupled case. As pipeline system and its support might add additional stiffness to the structure, response reduction factor which accounts for ductility, over strength and redundancy of a structure, will help to validate the results. ATC-19 provides with different formulae to calculate response reduction factor (R) for the structure. Pushover analysis is carried out for both coupled and decoupled case (empty condition), capacity curve results are further used to calculate response reduction factor.
R factor is a combined effect of over strength, ductility and redundancy (Patel and Shah 2010), Figure 9 illustrates the same (Figure 9).

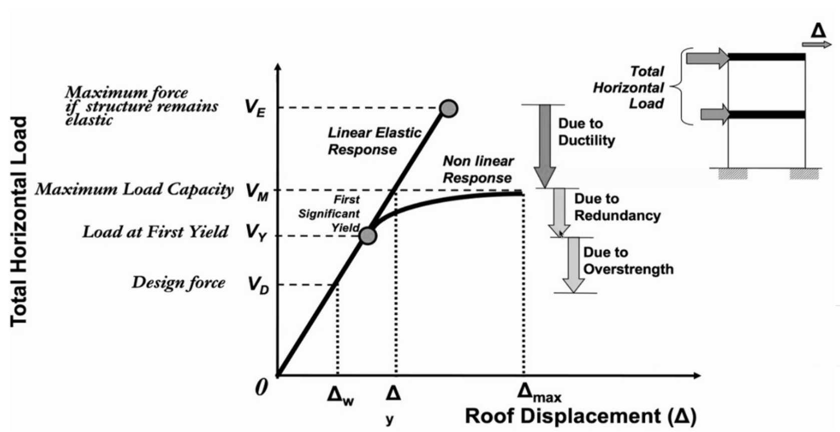


Figure 9 Concept of Response reduction factor (Rai and Jain 2019)

5.1 Design base shear using standard design spectrum

For computing design base shear value, standard design spectrum graph given in IS 1894 Part 4 (2015) is used, as shown in Figure 10, Figure 11 and Figure 12.

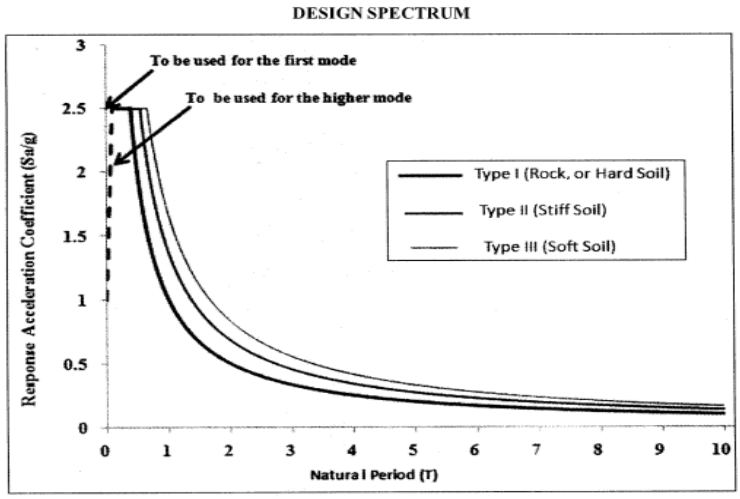


Figure 10 Spectral acceleration coefficient $\frac{Sa}{g}$

Seismic weight of the structure 1522 kN.
Time period for decoupled case (Empty condition) = 0.358.
Time period for coupled case (Empty condition) = 0.230
$\frac{Sa}{g}$ Value for both the given time periods will be same i.e. 2.5. Importance factor = 1.5
Z Factor = 0.24, multiplying factor for 2% damping = 1.4. R value for steel OMRF = 3
Design base shear (Vb) = $\frac{Sa}{g} * \frac{I}{R} * \frac{Z}{2}$ *1.4 = 319.62 kN.

5.2 Evaluating response reduction factor

In order to estimate response reduction factor, its components such as ductility, over strength and redundancy factor are calculated using capacity curve (base shear vs Roof displacement plot), which is obtained from carrying out pushover analysis in staad pro for both coupled and decoupled case (empty condition). Pushover analysis helps to determine the capacity of structure, here pushover analysis is carried out in z direction where maximum difference in base shear values were observed.

5.2.1 Calculations for evaluating R value

Over Strength factor (R_S) = $\frac{Vu}{Vd}$
Maximum Drift capacity Δm = 0.004 h = 0.004*7000 = 28 mm
Displacement ductility ratio (μ) = $\frac{\Delta m}{\Delta y}$, Δy yield drift from pushover curve
Ductility factor derived by Miranda and Bertero ($R\mu$) = $\frac{(\mu-1)}{\emptyset} + 1$
$\emptyset$ For medium soil = 1+ {1/ (12T- μT)} - {(2/5T)*R$\mu e^{-2(\ln(T)-0.2)^2}$}
Redundancy factor (R_R) = 0.71
Response Reduction Factor (R) = R_S* Rμ* R_R

6. Results and Discussions

6.1 Comparison of seismic responses for decoupled and coupled case

Dynamic analysis using Bhuj time history is carried out for both coupled and decoupled case. The seismic response such as modal frequency, storey displacement and base shear is recorded (Table 3).

Table 3 Staad Pro results for Modal Frequency

	Mode 1	Mode 2	Mode 3

Decoupled Case	..	..	..
Empty pipe condition	2.783	3.176	5.41
Operating pipe condition	2.470	2.80	4.782
Coupled Case	..	..	..
Empty pipe condition	4.330	6.413	7.493
Operating pipe condition	3.753	5.393	6.218

Table 4 ANSYS results for Modal Frequency

	Mode 1	**Mode 2**	**Mode 3**
Decoupled Case	..	..	..
Empty pipe condition	2.790	3.01	5.14
Operating pipe condition	2.490	2.70	4.60
Coupled Case	..	..	..
Empty pipe condition	4.340	6.363	7.448
Operating pipe condition	3.783	5.349	6.164

Above table 3 and table 4 represents the modal frequency results obtained for coupled and decoupled case. It shows that value of modal frequency has been increased in coupled case due to added stiffness of piping system and their support. Where coupled case with empty pipe condition has the highest values for modal frequency.

Table 5 StaadPro results for Base Shear

Decoupled Case	**X**	**Y**	**Z**
Empty pipe condition	171	1.049	118
Operating pipe condition	250	1.288	141
Coupled Case	**X**	**Y**	**Z**
Empty pipe condition	156	1.53	67
Operating pipe condition	188	1.48	81

Table 6 ANSYS results for Base Shear

Decoupled Case	**X**	**Y**	**Z**
Empty pipe condition	171.57	0.94	121
Operating pipe condition	249.3	1.00	142
Coupled Case	**X**	**Y**	**Z**
Empty pipe condition	157	1.543	67.6
Operating pipe condition	186.7	1.37	83

Table 5 and 6 represents the Base shear results obtained for coupled and decoupled case. Base shear values have been reduced for coupled case. In X direction value of base shear is reduced by 9% and in Z direction by 43%. Increased stiffness may result in increased R factor which affects design base shear values.

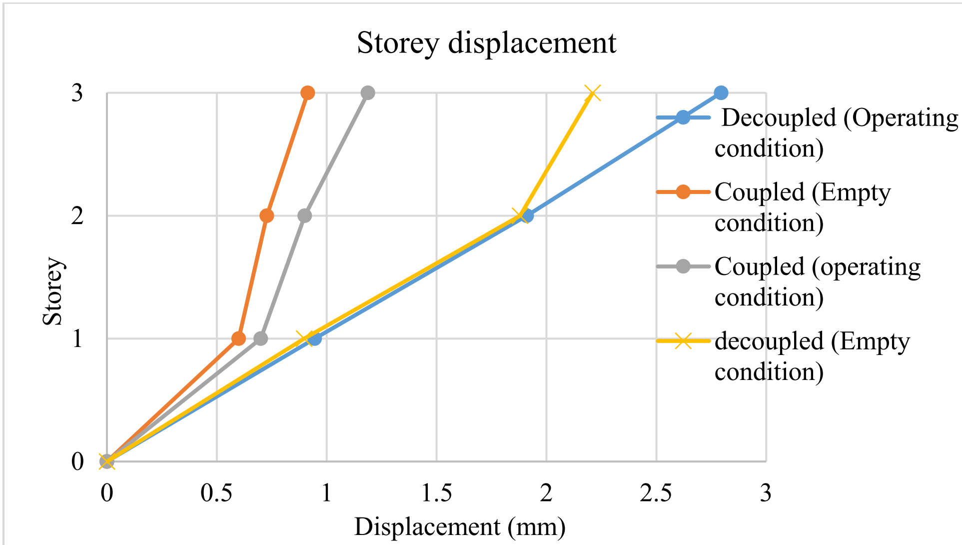


Figure 11. Storey displacement in X direction

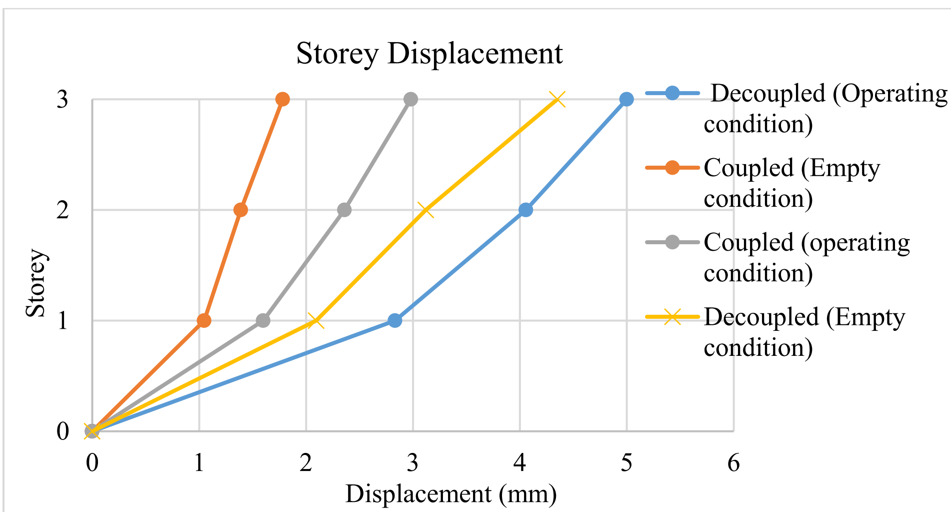


Figure 12. Storey displacement in Z direction

Max storey displacement is observed in decoupled case (operating condition) for both X and Z direction. This is due to increased seismic weight for operating condition which results in increased lateral forces.

6.2 Capacity curve and Response reduction factor

6.2.1 Pushover Analysis in Staad Pro.

Pushover analysis was carried out in staad pro for both the cases in z direction. It is observed from capacity curve that for the same roof displacement value in coupled case the value of base shear is more as compared to decoupled case, refer Figure 13 and 14.

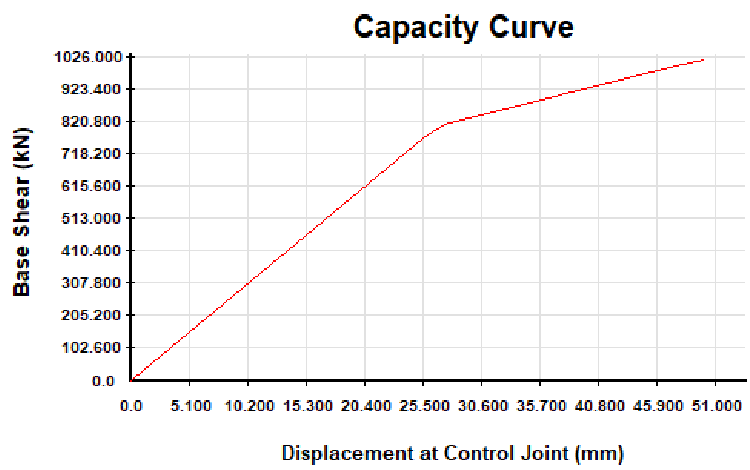


Figure 13. Capacity curve decoupled case

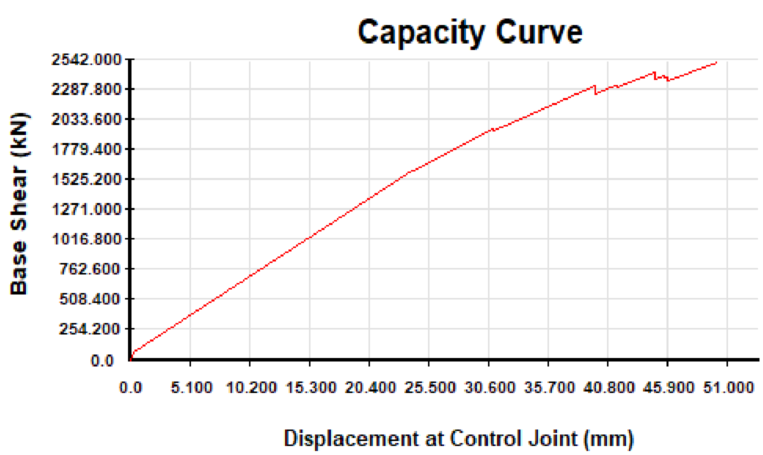


Figure 14. Capacity curve coupled case

6.2.2 Response reduction factor calculation for Coupled and Decoupled case.

Maximum Drift capacity Δm = 0.004 h = 0.004*7000 = 28 mm

Decoupled case

- Over Strength factor $\frac{Vu}{Vd} = \frac{1028}{319} = 3.23$
- Displacement ductility ratio (μ) = $\frac{\Delta m}{\Delta y} = \frac{28}{26.5} = 1.05$
- Ø For medium soil = 1+ {1/(12T- μT) }- {(2/5T)*$e^{-2(\ln(T)-0.2)^{\wedge}2}$} = 1.20
- Ductility factor Rμ = $\frac{(\mu-1)}{\emptyset} + 1 = 1.042$
- R = Rμ * Rs * R*R* = 1.042*3.23*0.71 = 2.4

Coupled case

- Over Strength factor $\frac{Vu}{Vd} = \frac{2542}{319} = 7.95$
- Displacement ductility ratio (μ) = $\frac{\Delta m}{\Delta y} = \frac{28}{24} = 1.167$
- Ø For medium soil = 1+ {1/(12T- μT) }- {(2/5T)*$e^{-2(\ln(T)-0.2)^{\wedge}2}$} = 1.395
- Ductility factor Rμ = $\frac{(\mu-1)}{\emptyset} + 1 = 1.119$

- R = Rμ * Rs * R*R* = 1.119*7.96*0.71 = 6.31

With reference to the above calculation value of R factor is greater for coupled case, due to increased stiffness.

7. Conclusion

In this study, an ethanol gas pipe rack was modelled, considering coupled and decoupled models, whose weight ratio exceeded 0.25 as per the clause given in IS 1893 part 4, for such structures both secondary (pipelines) and primary (pipe rack) are needed to be modelled. Here in this study four models were analyzed in ANSYS and Staad Pro, considering coupled and decoupled case for both empty and operating condition, and Pushover analysis was carried out in Staad Pro for evaluating response reduction factor.

The main findings of this case study are as follows:
In case of coupled model for both empty and operating conditions modal frequencies value increased by 35% as compared to decoupled case, this is mainly due to increased stiffness added because of pipelines and its support boundary conditions.

It was also observed that the values of base shear for coupled cases was reduced considerably (9% in X direction and 43% in Z direction), which can further direct towards the change in response reduction factor (R) for both the cases which may eventually reduce base shear values.
Pushover analysis was carried out to evaluate response reduction factor in Z direction, which resulted in giving higher (R) factor for coupled case in respective direction. Maximum roof displacement was observed in decoupled case (operating condition) but was within permissible limits. The results show that considering dynamic interaction while modelling and analysis of such structure is important as added stiffness and masses may affect the seismic response of the structure.

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