A Case Study: Dynamic Analyses of Barrette Foundations under a Pipe Rack in a High Seismicity Region

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Abstract: The need for transportation of fluids is increasing in recent years, calling for more complex analyses and design of the related facilities such as tanks, pumping stations, pipe racks, etc. If these are located in a high seismicity area and over a weak soil profile, the dynamic soil-structure-interaction gets even more difficult to deal with, considering the high number of unknowns and time constraints in most projects. In this paper, detailed dynamic analysis performed for the foundations of a pipe rack using finite difference software is presented. The pipe rack rests on single or braced barrette foundations in a drain column-improved soil profile. In each analysis, the variation of acceleration along the soil profile and maximum moment and shear force values on the foundation elements are calculated. The most critical section, from the dynamic point of view, is found as the braced barrette foundations resting on the region where drain columns are 37 – 41 m long. Another interesting aspect of the analyses is the variation in the barrette forces when their orientations were altered by 90°. Analysis results show that the moment and shear forces for the "old" transverse direction can be used in the longitudinal direction in the revised orientation of the four-barrette group.

Keywords: Dynamic soil-structure-interaction, transportation facilities, finite difference analysis, soil improvement with drain columns, barrette foundations.

1. Introduction

Design of fluid and gas transportation facilities located at high seismicity regions requires complex dynamic soil-structure-interaction (SSI) analyses. When these systems are located on relatively soft soil profiles, a comprehensive dynamic SSI analysis framework has to be developed, including carefully selected ground motion time series and sensitivity analyses for multiple important parameters. This contribution represents a state-of-the-art example for such complex cases: the results of the dynamic analyses of foundations for a 1307m-long, 7m-wide pipe rack supported by different foundation types sitting over an erratic soil profile is presented. As the pipe rack is a very long structure, it has been divided into 5 main blocks for the SSI analyses according to the changes in the soil profile and the structural requirements. In this paper, details of the analyses of two of the sections, 162 m-long Block 1 and 66 m-long Block 2, are discussed.

In these blocks, the pipe rack is supported by three different types of foundations, i.e., braced barrette foundations (consisting of 4 barrettes connected to each other), single barrettes, and the foundation at the intersection of the two blocks. Analyses for longitudinal and transverse sections along the pipe rack have been conducted. On the longitudinal cross-section, there are three different regions that may behave differently, considering the variable soil profile and patterns of drainage columns. Therefore, results from each of these three regions are considered for longitudinal section; whereas, the transverse section of only one region with the highest moment and shear force values among those three is conducted. The moment and shear values along the piles and barrette foundations are presented and discussed. Additionally, the changes in these values for the case when the orientation of the barrette foundations is altered by 90° are also presented in comparison with the previous foundation orientation.

2. Analysis Inputs: Idealized and Improved Soil Profiles, Ground Motion Selection

In the construction area, a number of geotechnical and geophysical tests including Standard Penetration Test (SPT), Cone Penetration Test (CPT) and PS Logging have been performed. According to the test results, the general soil profile consists of Fill (F), Silty Clay/Clayey Silt (SC-CS), Sand/Silty Sand (S-SS) and bedrock (Claystone / Siltstone / Sandstone; CSS) formations. The idealized soil profile and respective geotechnical parameters for the longitudinal (LS) and transverse (TD) cross-sections are presented in Table 1. The groundwater table is located just beneath the fill layer. The idealized soil profile models used for finite difference analyses of the longitudinal and transverse sections are presented in Figures 1 and 2, respectively. As shown in these figures, the thicknesses of the soil layers are variable along the pipe rack. For the dynamic analyses, the software FLAC2D v8.0 (Itasca Consulting Group Inc., 2016) which is based on finite-difference modeling is utilized. The standard fixities at the sides and bottom of the model have been used for the initial static part of the problem; whereas, the free field boundary condition has been used for the dynamic part to minimize the effects of the reflecting/refracting waves from the boundaries of the model.

Table 1. Soil parameters used in the finite difference analyses*

Layers	Elevation (m) LS	Elevation (m) TD	c' (kPa)	c_u (kPa)	ϕ' (°)	γ (kN/m^3)	G (MPa)	K (MPa)
F	0 – 2.5	0 – 3.5	1	-	30	19	104.1	225.4
S-SS_1	2.5 – 10.5	3.5 – 10	1	-	28	20	111.4	241.3
SC-CS_1	10.5 – 22.5	10 – 22	-	45	-	18	84.8	183.6
SC-CS_2	22.5 – 41	22 – 41.5	-	60	-	18	793.8	172
SC-CS_3	41 – 49	41.5 – 49.5	-	70	-	18	90.3	195.7
SC-CS_4	49 – 57	49.5 – 57.5	-	80	-	19	150.3	325.7
S-SS_2	57 – 68	57.5 – 69	1	-	33	21	349.6	757.4
CSS	68 – 80	69 – 85	249		31	25	1440.2	2400.3

**c': Effective cohesion, c_u: Undrained shear strength, ϕ': Effective internal friction angle, γ: Unit weight, G: Shear modulus and K: Bulk modulus*

To reduce the probable post-construction settlements and decrease the probability of liquefaction, drain columns and barrette foundations are designed for improving the soil conditions under the pipe rack. For this analysis case, the ground improvement is utilized with drain columns of 80cm-diameters with lengths varying between 28 to 41 m. Additionally; barrette foundations of 1.0m x 2.80m are constructed under the foundations due to settlement-related problems. The width of the barrette is parallel to the longitudinal direction of the pipe rack. The barrette foundation lengths are variable since they are embedded into the rock. These improved soil profiles are also presented in Figures 1 and 2 for the longitudinal and transverse cross-sections. The spacing of the barrette foundations is 6-18 m. In these figures, the drain columns are shown with light green and the barrette foundations blue. For the barrette piles, the structural element "pile" in FLAC 2D software is utilized in the analyses; whereas, the drain columns are modeled as strengthened soils as in the static part of the problem.

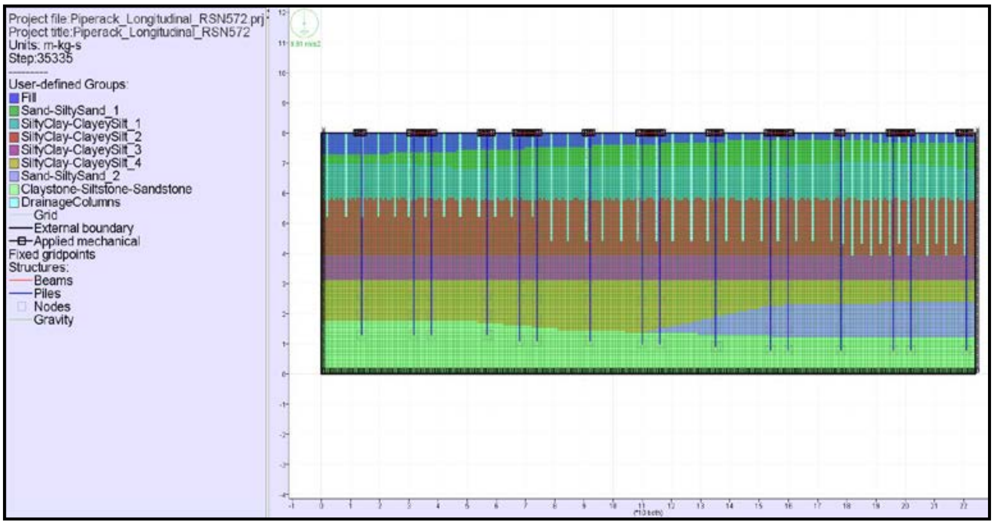


Fig. 1 - The drain columns and barrette foundations in the soil model for longitudinal cross-section

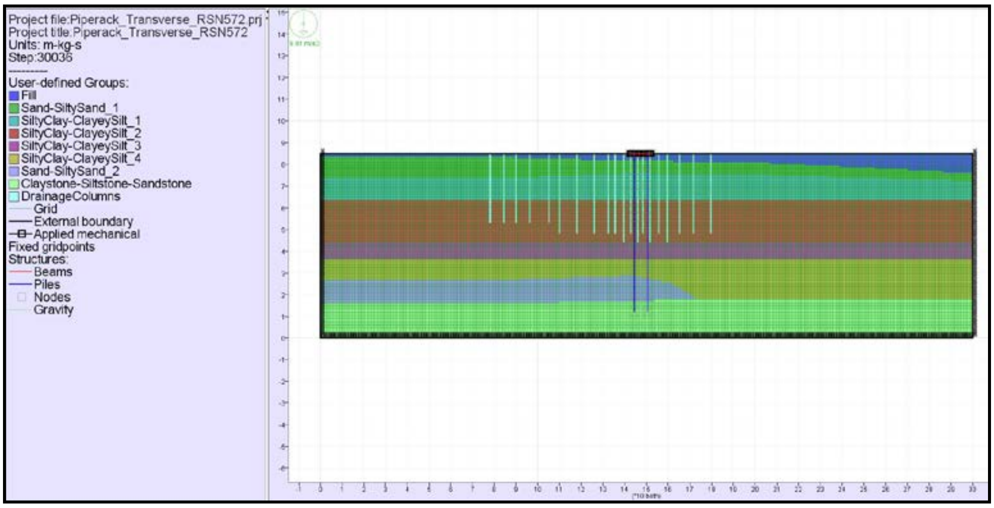


Fig. 2 - The drain columns and barrette foundations in the soil model for transverse cross-section

The construction site is located approximately 85 km away from an active fault system that was ruptured by large-magnitude (M>7) events in the last century. The site-specific probabilistic seismic hazard assessment (PSHA) of the site resulted in peak ground accelerations (PGA) of 0.23g for 475 years return period at the seismic bedrock. 11 ground motions are selected by using the Uniform Hazard Spectrum of the site, based on the guidelines given in Turkish Building Earthquake Code (2019) (Figure 3). Selected ground motions are scaled to match the PGA and the scale factors are presented in Table 2.

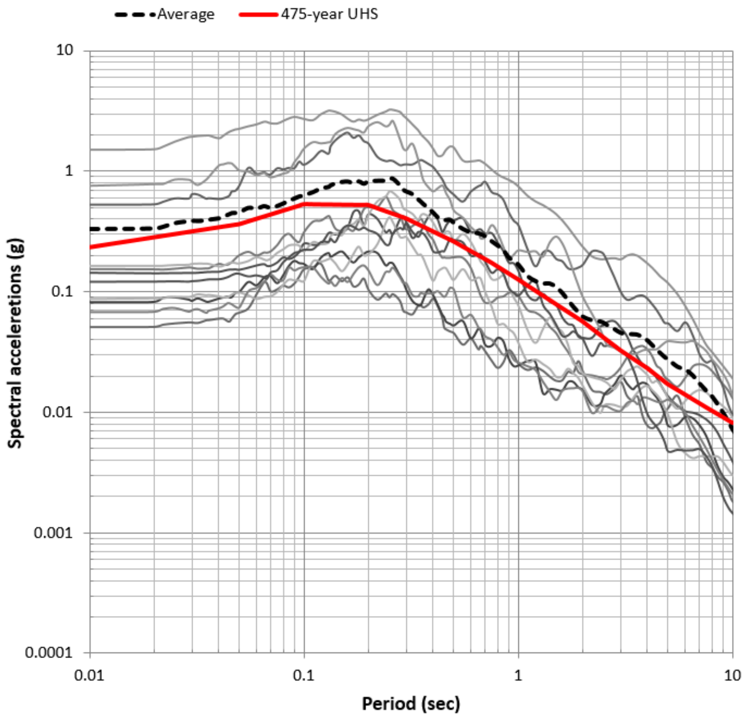


Fig. 3 - 475-years Uniform hazard spectrum of the site

Table 2. Selected ground motions and scale factors

Earthquake Name	Magnitude	Mechanism	Rec ID	R_{RUP} (km)	V_{s30} (m/sec)	Scale factor
Taiwan SMART1(45)	7.30	Reverse	572	51.35	671.52	1.62
Cape Mendocino	7.01	Reverse	825	6.96	567.78	0.15
Landers	7.28	Strike-slip	891	50.85	659.09	4.61
Landers	7.28	Strike-slip	897	41.43	635.01	2.83
Duzce_Turkey	7.14	Strike-slip	1612	4.17	551.30	1.51
Duzce_Turkey	7.14	Strike-slip	1618	8.03	638.39	1.43
Manjil_Iran	7.37	Strike-slip	1633	12.55	723.95	0.44
Hector Mine	7.13	Strike-slip	1795	50.42	686.12	2.65
Hector Mine	7.13	Strike-slip	1836	42.06	635.01	3.42
Darfield_ New Zealand	7.00	Strike-slip	6949	53.75	551.30	1.91
Duzce_Turkey	7.14	Strike-slip	8165	4.21	760.00	0.31

3. Discussion of the Analysis Results

Three different types of foundations exist under this pipe rack: (i) single (unbraced foundation), (ii) four-barrettes connected to each other with a slab (braced foundation), and (iii) two-barrettes connected to each other between two structural sections. The distributed loads from the superstructure are approximately 135 kPa and 74 kPa for cases (i) and (ii) whereas, for the connection between two structural sections (case iii), the load is 89 kPa. Moreover, lengths of the drain columns also change beneath these foundations so that, as mentioned previously, three different regions have been studied for that purpose: region of a) 28 m long drains, b) 36 m long drains and c) 37m&41m long (repeating) drains. Figure 4 shows the variation of maximum accelerations along the soil profile for the longitudinal section using 11 different strong ground motions mentioned previously. As can be seen from Figure 4, the maximum acceleration is 0.52 g at the surface, however it becomes 0.64 g at about 50m depth.

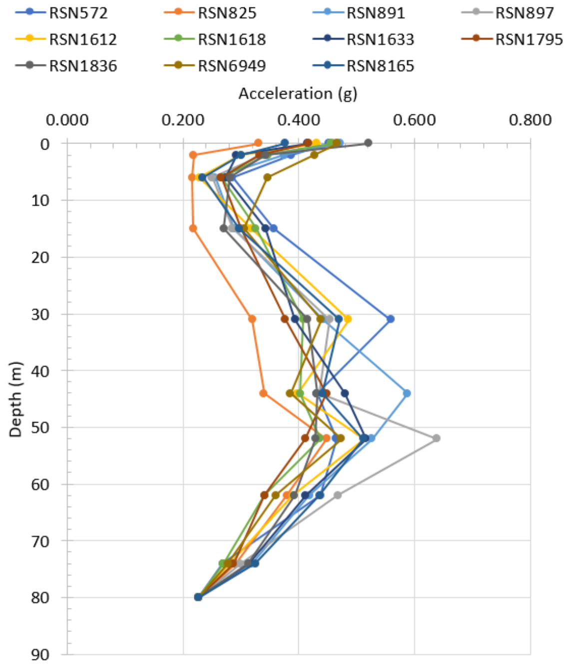
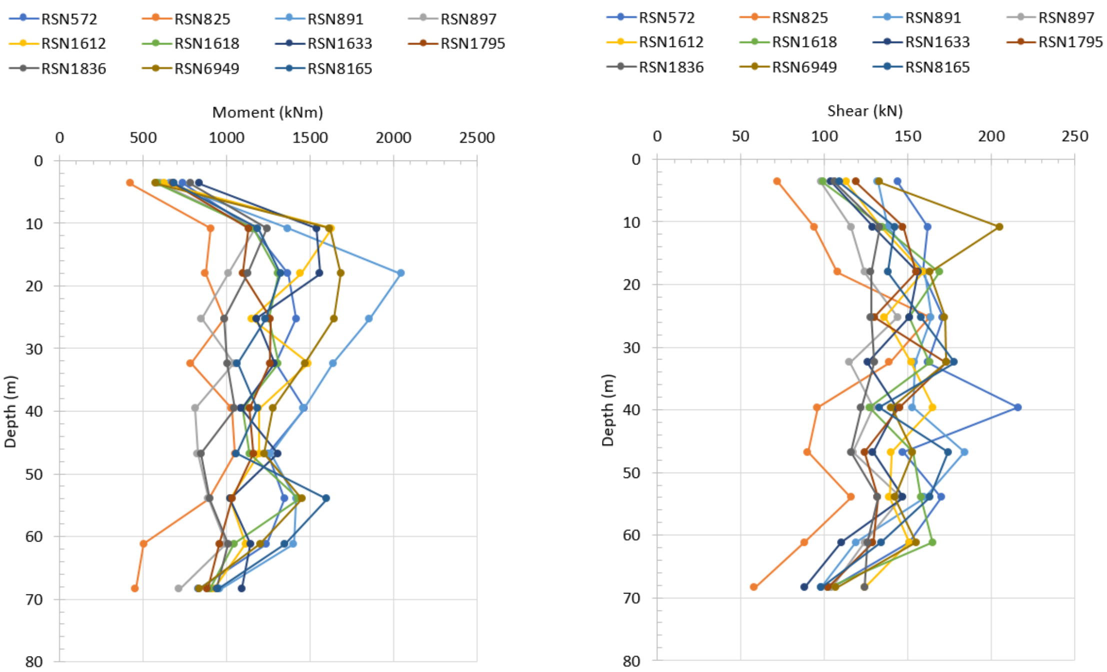


Fig. 4 - Variation of maximum acceleration along with depth for longitudinal cross-section

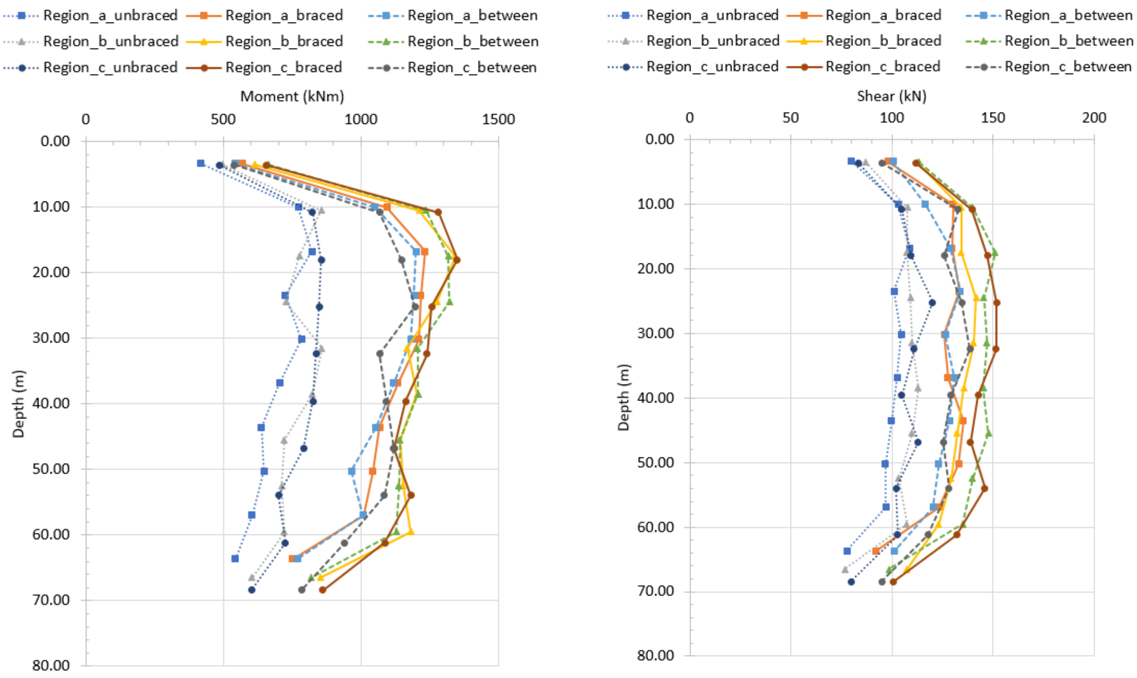
For the barrettes in each region mentioned previously, dynamic analyses results are evaluated. Figure 5 shows the variation of moment and shear forces for the region where the maximum average moment value is obtained for the barrette foundation (case ii). This maximum value is observed in the region of 37 m – 41 m long (repeating) drains for the braced foundation type.



(a) *(b)*

Fig. 5 - Variation of the maximum moment (a) and shear forces (b) for braced foundation along with depth for longitudinal cross-section

The results for other cases are not presented here due to page limitations, however, the average of the moments and shear forces of each foundation type as well as each region are presented in Figure 6.



(a) *(b)*

Fig. 6 - Comparison of the average moments (a) and shear forces (b) for different foundation types and regions

Figure 6 shows that moment and shear forces along with the barrettes for unbraced foundations are smaller than the other braced cases regardless of the lengths of the drain columns. However, the braced barrette foundations and the ones in the connection area between the two blocks are very close to each other.

3.1. Transverse Cross-Section

This part includes the analyses of the transverse cross-section including drains and barrette foundations together. For the transverse section, the analyses have been performed for only the most critical section and foundation type determined for the longitudinal section. The variation of maximum accelerations along the soil profile for the transverse direction for the same 11 strong ground motions are provided in Figure 7 whereas the moment and shear forces can be seen in Figure 8. When the Figure 7 is examined, it can be seen that the maximum acceleration is 0.516 g at the surface, however, it becomes 0.682g at about 45m depth which is very close to the longitudinal one.

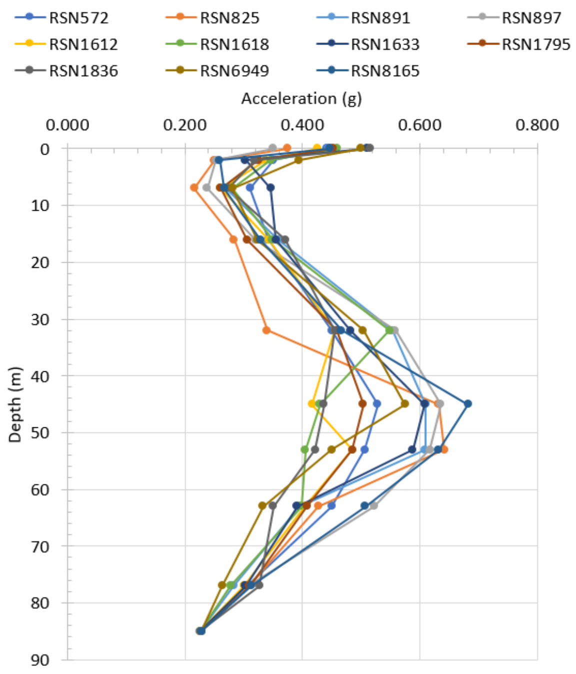
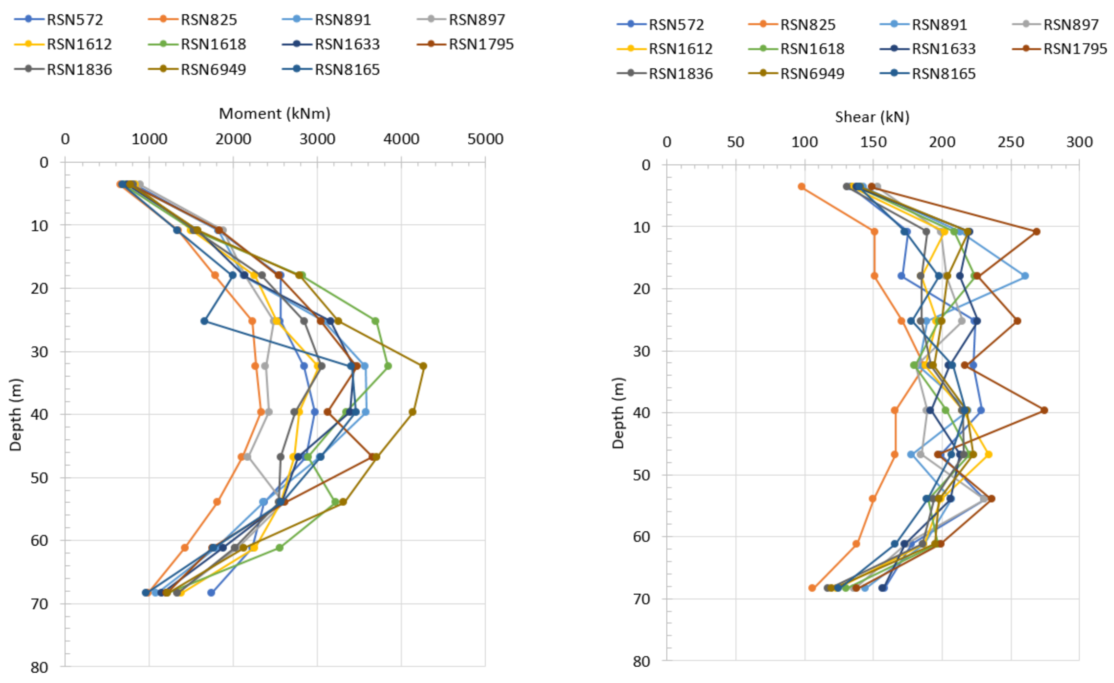


Fig. 7 - Variation of maximum acceleration along with depth for transverse cross-section



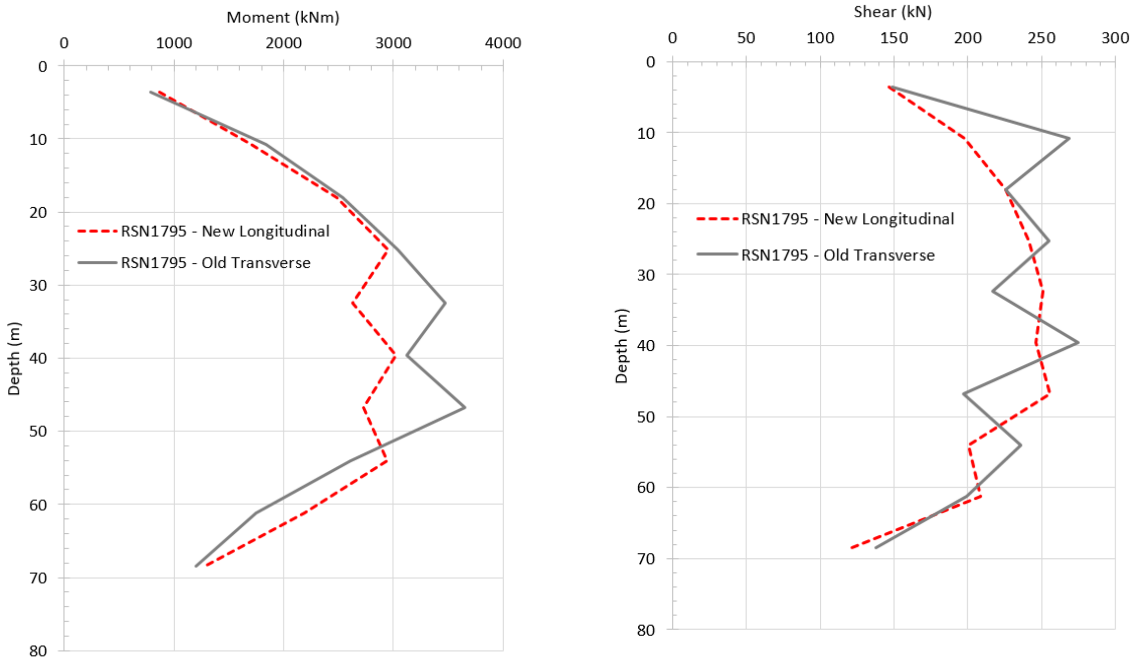
(a) *(b)*

Fig. 8 - Variation of the maximum moment (a) and shear forces (b) for braced foundation along with depth for transverse cross-section

3.2. Orientation of Barrette Foundation

This section tries to answer the problem of the variation of the values of moment and shear forces if the orientation of the barrette foundations changes by 90°, i.e., estimation without making more analyses to save time. The barrettes in the braced foundations have been rotated, whereas the other types remained the same in the new configuration. To see the difference after the orientations of the barrette foundations have been inter-changed (i.e., longitudinal braced becomes transverse), an earthquake resulting in an average behavior in terms of the moments has been selected and the analysis is performed with the new orientation using only the selected event. After that, the obtained results are compared with the values of the "old" transverse direction.

For braced (four barrette) foundations, as can be seen in Figure 9 below, the average moment and shear force values for the "old transverse direction" are very close to the "new longitudinal direction". This means that the values for the "old" transverse direction can be used in the longitudinal direction in the revised orientation of the barrettes of four.



(a) *(b)*

Fig. 9 - Comparison of (a) moment and (b) shear forces for four barrettes connected to each other for old and new configurations

4. Conclusions

This contribution represents a state-of-the-art example for a very long pipe rack resting on a weak erratic soil profile in a high seismicity region. The foundation system of the pipe rack varies along its length including barrette foundations and drain columns. A detailed SSI analyses has been conducted which includes two-dimensional longitudinal and transverse direction analyses of the complete system, i.e., soil layers, drain columns and barrette foundations together. The structure over the foundations has been included as distributed load. The results are presented in terms of moments and shear forces along the barrettes as well as the acceleration values along the soil depth.

For all types of barrette foundations, the maximum moment and shear force values for longitudinal and transverse sections are summarized in Table 3 below.

Table 3. Comparison of the obtained results

Barrette type	Moment (kNm)		Shear Force (kN)	
	Maximums	Average	Maximum	Average
Single barrette	1511	855	154	120
Four barrettes	2046	1349	216	152
Between structural sections	1916	1321	196	151
Transverse direction	4267	3232	275	213

It was seen that; the maximum moment and shear values, from the longitudinal section, are obtained for the case of braced foundations where four barrettes are connected each other. For this type of foundation where the most critical results are observed, maximum and average values of the moment and shear forces under each region are presented in Table 4 below.

Table 4. Results for the most critical case

Region	Moment (kNm)		Shear Force (kN)	
	Maximum	Average	Maximum	Average
Drain lengths of 28 m	1830	1233	195	135
Drain lengths of 36 m	2044	1342	169	142
Drain lengths of 37-41m (repeating)	2046	1349	216	152

Last but not least, after the orientation of the barrette foundations has changed, it was seen that the moment values have also switched between the “old” and the “new” orientation configuration. As a fact, project durations are very limited in most of the times and the time required to perform such detailed dynamic analyses is often too long compared to it. Therefore, it is proven that the values can be used interchangeably without making more analyses if a revision is required in the project design.

References

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