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Performance assessment of RC petrochemical pipe racks including SSI-effects

Luigi Di Sarno[a,b], George Karagiannakis[a]
[a] *Department of Engineering, University of Sannio, Piazza Roma n.21, 82100 Benevento, Italy*
[b] *Department of Civil Engineering and Industrial Design, University of Liverpool, Brownlow Hill, L69 3GH Liverpool, UK*

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ABSTRACT
The high demand for seismic resilience in modern communities makes the integrity of petrochemical plants necessary. Although the seismic risk that process plants exhibit to humans and environment is rather high, modelling and design aspects of pipe racks such as the coupling effects between structural members and supported equipment as well as soil-structure interaction effects along with seismic input uncertainty are not sufficiently addressed in seismic codes resulting in unsafe and unjustifiable design by engineers. The present study examines the seismic performance of a RC Liquified Natural Gas pipe rack being coupled and decoupled with several pipelines accounting for soil deformability. A surface foundation was adopted, and the soil was modelled with linear and nonlinear springs and dashpots. The dynamic coupling as well as soil-structure interaction deteriorated the response of structural and nonstructural members as well as altered the dispersion of intensity measure at which limit state exceedance was observed. This may be an indication that seismic codes, particularly European ones, should consider the dynamic coupling and soil nonlinearity more normatively.

1 INTRODUCTION

The position of mid-stream facilities is a strategic choice that accounts for the safe and economical transportation of natural gas from the feedstock region to the processing area. Process plants should remain intact after being struck by natural hazards the frequency and severity of which is increasing due to the climate change. A failure within mid- and down-stream facilities could pose human life at risk and cause severe repercussions to the plant and nearby communities. To this effect, modern societies implement strategy execution plans that encourage preventive actions e.g. research endeavours for safety design or emergency response planning. The seismic hazard, which the present work intends to examine, is a highly accountable one among others in European Union considering that ample process plants are located in seismic-prone countries e.g. Italy, Portugal and Greece.

Each structure within oil and gas industry has a pivotal role and it is interconnected with other units via pipelines. Pipe Racks (PRs) included in oil and gas refineries are served so as to support pipelines that transfer combustible and/or toxic substances from one process unit to another. The dynamic interaction between the rack and other nonbuilding structures and/or nonstructural components may alter extensively the seismic response of PRs and this is why different design and analysis methodologies are usually applied compared to common building structures. The main European contribution for seismic-resistant design (EN 1998-1 2004) do not make reference to PRs whereas the American one (ASCE/SEI 7-16 2017) along with the guideline (ASCE 2011) are more informative and address the issue of dynamic interaction between supported equipment and supporting structure. In particular, the latter code and guideline define a weight ratio W between the supported equipment and supporting structure; if the ratio is greater than 25% the dynamic interaction (coupled case) is accounted for the analysis, otherwise it is neglected. Aside from the ratio, the American codes define a vibration period T threshold value of 0.06s regarding the rigidity of connection between nonbuilding structures not similar to buildings and supporting structure. In case a supported structure has vibration period less than the 0.06s, it can be considered as rigid component. It is noteworthy that the above analysis criterion is not precise since the fixed value of 25%, which indents to introduce some nonlinearity for Peak Floor Acceleration deamplification, is applied independently of structural archetype. Also, the code addresses only the rigidity of connection of nonbuilding structures with the supporting one without dealing with the relative stiffness of pipe support with the pipeline that is multiply supported, and thus local vibration modes of pipes may change the response of PRs or cause loss of containment events.

The research on the seismic response investigation of PRs that assess the above-mentioned analysis criteria is rather obscure (Di Roseto et al. 2017). Parametric analyses on a piping system and PR by considering different weight ratio W, end conditions of pipes and diameter of link elements were conducted in (Azizpour and Hosseini 2009). The analyses demonstrated that the frequency of the entire system could be affected more by the end-conditions of pipes and pipe link elements than the weight ratio. This outcome emphasizes the fact that additional to weight ratio analysis parameters should be taken into account when analysing multiply supported pipelines. Of course, further research is needed on this topic by quantifying the influence in terms of PR Inter-storey Drift Ratio (IDR) and pipe stress development.

In virtue of convenience in transportation, the mid- and down-stream facilities are usually located at seaside where the soil is liquefiable and may affect the seismic response. According to the findings in the literature, Soil-Structure Interaction (SSI) effects are more profound on squat and heavy structures by increasing the lateral deformation and lessening the force demand (Elnashai and Di Sarno 2015). Even though SSI phenomenon has been mainly examined for liquid storage tanks and nuclear containment structures, PRs could also be heavy and stiff depending on the supported equipment and the connection with other nonbuilding structures and nonstructural components. For instance, in case the supported equipment is flexibly supported, the higher-induced displacement by the SSI may increase the strain of the most critical and irregular components e.g. elbows or T-joints. Seismic design codes permit a reduction in seismic design forces in the equivalent lateral force or modal response spectrum analysis by using the effective damping of soil-structure system B_{SSI}. More information about the modified response spectrum for the flexible base case can be found in (NEHRP 2015) and (Mylonakis and Gazetas 2000).

The literature abounds with models that attempt to describe the soil-foundation response. Except for the rigorous finite element representation, it is generally acceptable by the code provisions the calibration of soil deformability beneath shallow foundations with frequency-independent point or surface springs being modelled at the fundamental period of the structure. For this purpose, the impedance function is formed for each vibration mode as described in the sequel. Pile foundation is a common choice in oil and gas industry for increasing the lateral resistance and minimising the foundation settlement. This foundation type is being investigated by the Authors and will not be described in this work. Finally, the soil nonlinear behaviour in the near-field could yield in significant alteration of structural demands. (Bolisetti et al. 2018) illustrated that primary (nonlinear site response) and secondary (at the foundation) nonlinearity may lead to unconservative superstructure response prediction, and thus should be considered in buildings if accurate estimates of loss are required.

At least to the Authors' knowledge, there is no fragility analysis framework that addresses the seismic reliability of PRs as it has been done partially for common buildings (Anvarsamarin et al. 2018) and other nonbuilding structures e.g. bridges (Kwon and Elnashai 2007) accounting for SSI effects. The present work intends to shed some light on PRs seismic performance when accounting for SSI and dynamic interaction by considering as a testbed a RC pipe rack. Previous studies have shown that numerous uncertainties exist when analyzing the seismic performance of a structural system relating mainly to modelling (epistemic) and seismic input (aleatory) (Dolsek 2009; Kwon and Elnashai 2006). The epistemic uncertainty may have different influence far or near to collapse damage state and the record-to-record randomness may increase the dispersion of Intensity Measure (IM). These facts are missing from process plant structures due to the limited research in the literature. Before examining epistemic and aleatory uncertainties, some general aspects of seismic response analysis of PRs is preceded.

2 SEISMIC RESPONSE OF PIPE RACKS

Pipes racks are characterised as nonbuilding structures similar to buildings in (ASCE/SEI 7-16 2017) because they are not used for domestic purposes yet to support industrial equipment and the seismic behaviour could present several dissimilarities and be assessed in a similar fashion to common buildings. The Performance-Based Design (PBD) or Limit States (LSs) design could find application to PRs towards designing more safely and financially efficient industrial plants. A traditional prescriptive design approach and PBD were compared in (Di Roseto et al. 2017) upon a modular PR and it was concluded that PBD was more safe and financial efficient since different types of uncertainties can be quantified and prevented in a rational manner and the required performance can be achieved in advance for the lifespan of the PR. It is a common engineering practice that PR should remain elastic, however, high Peak Floor Acceleration (PFA) with resonance phenomena could be observed.

Pipes racks come in various forms depending the process plant type e.g. oil or gas refinery, and thus the seismic response may differ substantially. For instance, mass, stiffness and geometrical irregularities are a common case that most of the time requires the dynamic analysis of PRs accounting for local modes due to suspended equipment; however, static analysis may be appropriate when nonbuilding structures are governed by the first vibration mode. One of the key aspects of PRs seismic performance pertains to the modelling and design of nonstructural components and other nonbuilding structures not similar to buildings. The type of connection, either flexible or rigid, of equipment with the supporting structure as well as the configuration of piping system on the rack that commonly includes bent parts for introducing some flexibility are common consideration when modelling a rack. Also, it is a common practice addition load to be distributed on pipe supporting beams for further installation. The ratio W is one among other indicators e.g. rigidity of connection or local mode effects for dynamic coupling consideration. The Boundary Conditions (BCs) of pipes constitute a decisive parameter for the system performance as it is demonstrated in the following Case-Study (CS).

3 SEISMIC ASSESSMENT METHODOLOGY

The seismic assessment methodology of a RC concrete rack including in Liquified Natural Gas (LNG) terminal is presented. In contrast with the initial design, the rack was placed in a high-seismicity zone in order the performance of structural and nonstructural components to be highlighted. The rack is 102 m long because it serves to transfer ethylene from the tank (next to short rack in the transverse direction) to the nearby process units and it was modelled on (SeismoSoft 2018) (Figure 1). More information about geometrical and mechanical properties of the rack can be found in (Bursi et al. 2018; Di Sarno, L., Karagiannakis 2019a). The rack supported 7 pipelines with different diameter varying from NPS 4 to 16 that will be analysed in the following by considering (coupled) and neglecting (decoupled) the dynamic interaction.

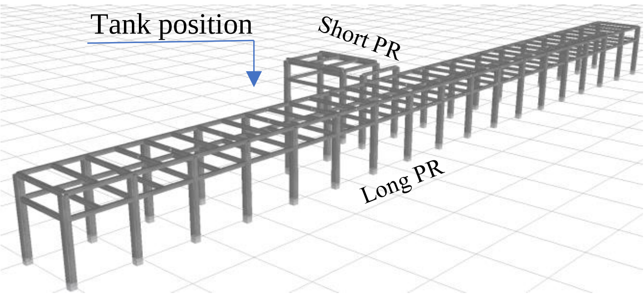

Figure 1. The RC rack model on (SeismoSoft 2018)

3.1 Modelling

The RC rack weighs roughly 533 tonnes and pipelines weight constitutes the 4% (W) of the entire system weight. According to ASCE 7 criterion, the piping system can be analysed separately from the rack, however, both cases will be considered in the following in order to highlight the influence of pipes BC consideration on pipe rack. To acquire a better insight of piping system performance, the BCs were not modified; thus, fixed, pinned and rollers are considered (Figure 2). It is noteworthy that in the decoupled case only the inertia effects of pipes are considered whilst the differential movements of pipe supports and the inertial effects of pipes on the rack are neglected. Due to the high computational effort needed to perform analyses in the decoupled case, only 2 (with the lowest and greatest diameter) out of 7 pipelines are analysed in the following, however, the inertia effects of all pipes were considered in the coupled case.

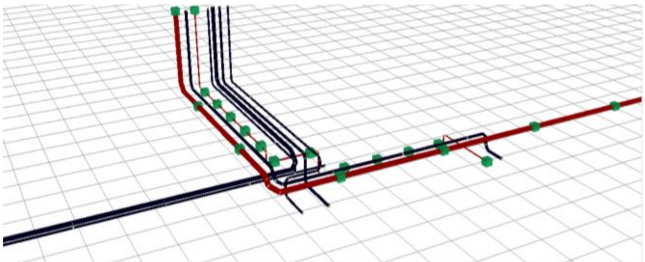
Figure 2. The piping system model in (SeismoSoft 2018). The BCs are also highlighted with green.

Furthermore, a surface foundation is considered for the RC rack. The bearing capacity of the soil, which is categorized as soil type C in EN 1998-1 (2004) with V_s=210 m/s, as well as the surface foundation that consists of centered footings and strip beams were checked under axial, bending and shear loading according to Fardis (2009) after placing the structure in Priolo Gargallo, Sicily. The soil was modelled with point springs placed both under the footings and strip beams. For this purpose, the dynamic impedance functions were used, which have the following formulation:

$$\mathcal{K}_j = \frac{\bar{P}_j}{\bar{u}_j} = \bar{K}_j + i\omega C_j \quad (1)$$

where $\bar{P}_j$ and $\bar{u}_j$ is the amplitude of excitation force and structural response, respectively; $\bar{K}_j$ is the dynamic stiffness that reflects the stiffness and inertia of the supporting soil; C_j is the radiation and material damping, and ω is the excitation frequency. The impedance function is formed for each vibration mode j (3 translational and 3 rotational) based upon the formulae provided by (Mylonakis et al. 2006). The stiffness of springs in two translational (vertical (z) & longitudinal (x)) as well as rotational direction (around y axis) for the footing (F) and strip beams (S) are given in the following Figure 3.

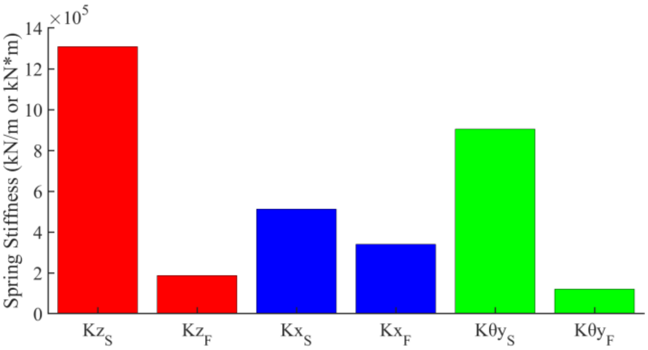

Figure 3. Representative values of footing and longitudinal strip beam stiffnesses (S: Strip beam, F: foundation)

Soil nonlinearity is introduced as well according to the availabilities of the software. Therefore, the Ramberg-Osgood model is calibrated to take the soil hysteresis into account without considering strength degradation. The model is calibrated with the Root Mean Square Error (RMSE) method and the calibrated curves are shown in Figure 4.

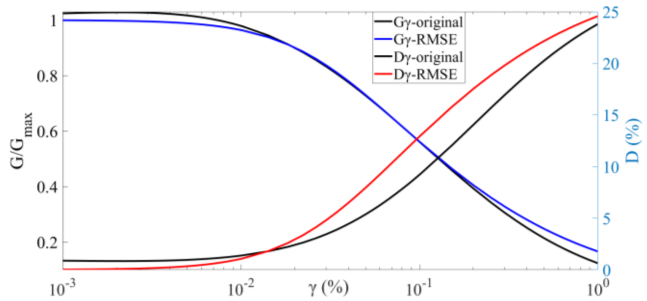

Figure 4. The RC rack model on (SeismoSoft 2018)

3.2 *Incremental dynamic analysis*

Before the analysis of PR, a fundamental step for the assessment process is the performance levels determination both for the RC members and steel pipelines. Two failure modes were considered for both types; regarding the former one, failure in shear and bending were defined whereas for the latter, failure under tensional and local buckling were determined. The interested reader could find more information for the damage states in (Fardis 2014; Di Sarno, L., Karagiannakis 2019b; Vathi et al. 2017).

The analysis of PR was conducted via the Incremental Dynamic Analysis (IDA) using 18 records, near- and far-field, as shown in Figure 5. The number of runs was dependent on each record; the initial one was determined roughly at 0.05g and step increments of 0.05g for $a_g \leq 1g$ and 0.1g for $a_g > 1g$ were employed. The scaling factor was applied both for the horizontal (H) and vertical (V) component in order to keep the ratio V/H constant. The same procedure was considered for the case with SSI (W/ SSI).

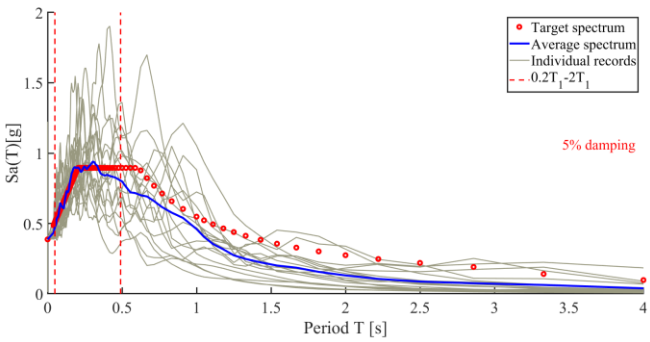

Figure 5. The RC rack model on (SeismoSoft 2018)

4 FRAGILITY ASSESSMENT - RESULTS

The fragility analysis of process plant structures, and particularly of PRs, is rather obscure in the literature (Di Roseto et al. 2017). Although PRs could be rather complex systems due to the supported equipment leading to unpredicted seismic behaviour, there is currently no literature that investigates this subject accounting for uncertainties in the modelling e.g. analysis methodology or SSI.

The fragility was derived considering lognormal Cumulative Distribution Function (CDF) for IM (Y=lnX) and Maximum Likelihood Estimation (MLE) for the curve fitting. In more details, the lognormal CDF is given by:

$$P(C|IM = x) = \Phi\left(\frac{\ln\left(\frac{x}{\theta}\right)}{\beta}\right) \quad (2)$$

where P(·) is the conditional probability of LS exceedance given the IM, Φ is the lognormal CDF and θ, β are the median and standard deviation, respectively. The MLE relies on the maximization of a likelihood function that under the statistical model the observed data is most probable. If m is the number of records that caused collapse and n-m the number of records that did not cause collapse, then the probability the entire set being observed is given by:

$$L = \prod_{i=1}^{m} L_{Ci} \cdot L_{NC}^{n-m} \tag{3}$$

where L_{Ci} is the normal Probability Density Function (PDF) that an individual record causes LS exceedance at a specific IM_i and it holds:

$$L_{Ci} = \varphi\left(\frac{\ln\left(\frac{x}{\theta}\right)}{\beta}\right) \tag{4}$$

Also, L_{NC} is the likelihood that a ground motion will be scaled up to IM_{max} without causing collapse and it holds (complementary CDF):

$$L_{NC} = 1 - \Phi\left(\frac{\ln\left(\frac{x}{\theta}\right)}{\beta}\right) \tag{5}$$

Finally, the Equation 3 occurs taking into account the multiplication theorem.

4.1 Structural members

The FFs were estimated first for the structural members W/O and W/ SSI accounting for dynamic coupling as well. According to the results shown in Figures 6-9, the linear soil increased mildly the fragility of columns, while the influence was greater for the beams at higher IM levels. Also, it was observed that soil nonlinearity decreased the dispersion of IM that caused damage to structural members and this might be an indication that soil energy dissipation made structural response independent of modelling. This is not a general conclusion, and thus cannot be applied to other PR systems necessarily. Finally, the dynamic interaction between the pipes and the PR caused significant soar of beams fragility e.g. from 18% to 41% at SLLS and PGA.

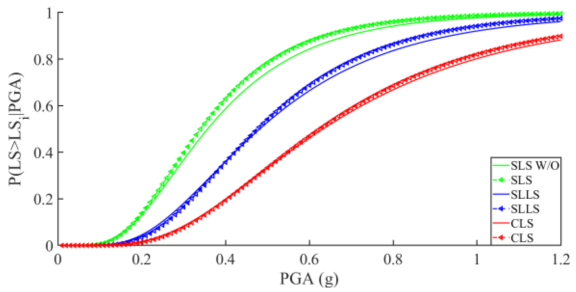

Figure 6. FFs for columns W/O & W/ SSI (linear) in decoupled case.

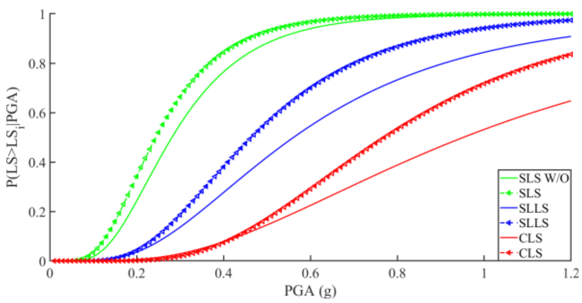

Figure 7. FFs for beams W/O & W/ SSI (linear) in decoupled case.

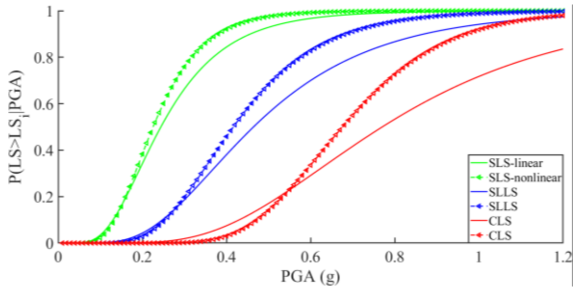

Figure 8. FFs for beams W/ linear and nonlinear SSI in decoupled case.

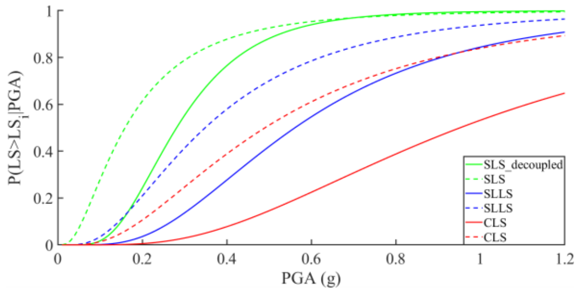

Figure 9. FFs for beams W/O SSI in decoupled and coupled case.

4.2 Nonstructural members

The seismic fragility of pipelines was also assessed and the FFs are presented in Figures 10-12. It is more informative and precise, the fragility curves to be provided with confidence levels. To this effect, the reader/risk analyst may have a better perception of true probability range that could be essential for further analysis and decision-making. For this purpose, the step Empirical Cumulative Distribution Function (ECDF) along with the 95% confidence levels derived from Greenwood's formula are provided in Figure 10. The negative effects of soil deformability are illustrated on Figure 11 where the probability of SLLS exceedance at PGA comes from 22% up to nearly 30%. It is worth mentioning that the dispersion of IM was lower for pipes compared to structural members and this might be due to the BCs governance on the seismic response. The effects of dynamic interaction on pipelines is mild compared to beams. Probably, this outcome occured from the fact that inertia effects of pipes acted as a safe-pad to dynamic coupling. Of course, the above drawn deductions cannot be generalized to other PRs due to the assumptions that were made e.g. BCs of pipes or soil modelling.

Overall, the uncertainties in modelling and soil-structure interaction indicated that the seismic performance estimation is not straightforward, let alone when more complex systems like the pipe rack in-hand are considered. Thus, a lot of research is required towards minimising different uncertainty sources that could further decrease the required cost for the stakeholders.

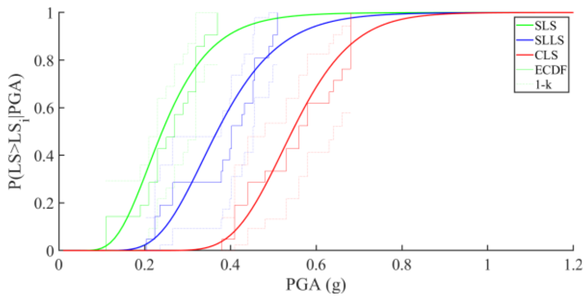

Figure 10. Pipes W/O SSI, decoupled, Greewood's 95% confidence level (k=0.05).

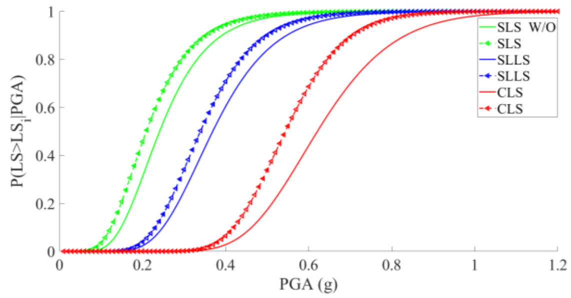

Figure 11. Pipes W/O & W/ linear SSI in decoupled case.

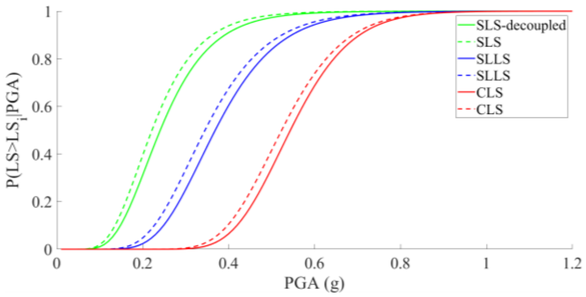

Figure 12. Pipes W/O & W/ SSI (coupled -decoupled).

5 CONCLUSIONS

The present study emphasized that dynamic coupling, soil modelling and deformability may alter considerably the seismic response of pipe rack – piping systems. In more details, the seismic fragility analysis resulted in the following conclusions:

- the soil-structure interaction deteriorated the system response both for structural and nonstructural members.
- Dispersion reduction was observed both when dynamic coupling and soil nonlinearity were considered making the system independent to modelling.
- the dynamic coupling deteriorated the system response e.g. from 18% to 41% at PGA and SLLS. The increase was lower for the pipelines due to the partial incompatibility of pipes with the rack.

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