# EFFECT OF SOIL-PILE-STRUCTURE INTERACTION ON NONLINEAR RESPONSE OF JACKET TYPE OFFSHORE PLATFORMS THROUGH INCREMENTAL DYNAMIC ANALYSIS

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## ABSTRACT :

The response of a fixed offshore tower is greatly affected by nonlinear behavior of the supporting piles. Pile-Soil-Structure Interaction (PSSI) can significantly affect the seismic performance of structures. The pile-soil interaction during earthquake loading is one of the most important sources of nonlinearity of offshore platforms.

Incremental Dynamic Analysis (IDA) is an emerging analysis method that offers thorough seismic demand and capacity prediction capability. This involves performing a series of nonlinear time history analyses under a suite of ground motion records by equally scaling both components of each record to several levels of intensity and recording the structural response.

This paper presents an efficient method to specify the effect of Seismic Soil-Pile-Structure Interaction (SSPSI) on structure through IDA method and shows suitable length to model offshore with equivalent dummy piles for more accuracy. Three-dimensional finite element model of offshore, jacket with both equivalent dummy piles (pile stub) and true piles considering soil-pile-structure interaction are subjected to Incremental Dynamic Analysis and the results of both are compared in terms of IDA curves.

In this paper, a computer program for Nonlinear Earthquake site Response Analyses of layered soil deposits (NERA) is used for nonlinear response of soil layers. Modeling of structure of offshore with its pile is performed with a FEM program (OpenSees) considering the effects of pile-soil-structure interaction using p-y curves.

**KEYWORDS:** Jacket Platform, Incremental Dynamic Analysis, Pile-Soil-Structure Interaction, Euivalent Dummy Piles.

## 1. INTRODUCTION

In recent years experimental and analytical investigations have been directed toward evaluating inelastic behavior of jacket type offshore structures subjected to strong ground motions. [1] Earthquake design of offshore platforms in seismic active areas is one of the most important parts in offshore platforms design. Dynamic response of piles in offshore platforms is a function of the characteristics of the loading, dynamic pile-soil interaction behavior and dynamic characteristics of the piles structural system. The SSPSI (Seismic Soil-Pile-Structure Interaction) analysis is the main step in evaluation of seismic behavior of pile supported offshore platforms. The pile-soil interaction problem during earthquake loading is one of the most important sources of nonlinear dynamic response analysis of offshore platforms. [2] incremental dynamic analysis (IDA) is a promising method that has recently risen which involves performing nonlinear dynamic analyses of the structural model under a suite of ground motion records, each scaled to several intensity levels designed to force the structure all the way from elasticity to final global dynamic instability [3]. Kimiaei.M et al. [2] has analyzed nonlinear response of offshore piles under seismic loads. They used BNWF model for the modeling of pile-soil interaction and finite element method for the modeling of jacket members in nonlinear range of deformation. Asgarian.B & Ajami.A [4] have surveyed dynamic behavior of jacket type offshore platforms through incremental dynamic analysis.

In this paper, the effect of considering Seismic Soil-Pile-Structure Interaction (SSPSI) on structure nonlinear seismic response was investigated by comparing with equivalent dummy piles model. For this purpose analysis of an existing sample offshore platform in Persian Gulf with Soil-Pile-structure interaction and equivalent dummy piles subjected to strong ground motions has been performed and the results in terms of peak interstory drift ratio of platform in IDA curves have been presented. This model has been developed using OPEN System for Earthquake Engineering Simulation (OPENSEES) [5] software. In order to analyze the variations in soil layers response against earthquake, "NERA" software [6] is used. In this software the nonlinear strain-stress behavior has been modeled and the relative displacements (or accelerations) in each sublayer have been calculated. [7]

## 2. INCREMENTAL DYNAMIC ANALYSIS

The Incremental Dynamic Analysis (IDA) [8], is a computer intensive procedure that offers thorough (demand and capacity) prediction capability by using a series of nonlinear dynamic analyses under suitably multiply-scaled ground motion records. It can estimate accurately the seismic performance of structures.

Applying IDA to determine the performance of a structure requires several steps. First, a proper nonlinear structural model needs to be formed, and a suite of records must be compiled. Then, for each record, the scaling levels must be selected, the dynamic analyses run and the results post processed. Thus, IDA curves of the structural response can be generated, as measured by a Damage Measure (DM, e.g., peak roof drift ratio $\theta_{roof}$ or $\theta_{max}$), versus the ground motion intensity level, measured by an Intensity Measure (IM, e.g., peak ground acceleration, PGA, or the 5%-damped first-mode spectral acceleration $S_{a(T1,5\%)}$). In turn these are interpolated for each record and summarized over all records to estimate the distribution of demand DM given intensity IM.

## 3. PILE-SOIL INTERACTION ANALYSIS USING BNWF

BNWF models used to analyze the dynamic response of piles should allow for the variation of soil properties with depth, nonlinear soil behavior, nonlinear behavior of pile-soil interfaces and energy dissipation through radiation and hysteretic damping. Special attention must be given to the evaluation of the free-field excitation. The computed ground motion at different levels within the soil is then applied to the nodal boundary supports representing the support motions [2]. Figure 1 shows the general view of a BNWF model and its main components in dynamic nonlinear response analysis of piles. [9]

In the present study, the soil stiffness is established using the p-y curve (lateral soil resistance versus lateral soil deflection) approach. The procedures for generating p-y curves proposed by Matlock et al [10], Reese et al [11] and O’Neil [12] are recommended by the American Petroleum Institute and are widely used in both research and professional jobs (API-RP- 2a) [13]. Therefore in this study, the soil stiffness is modeled employing the static p-y curves recommended by API.

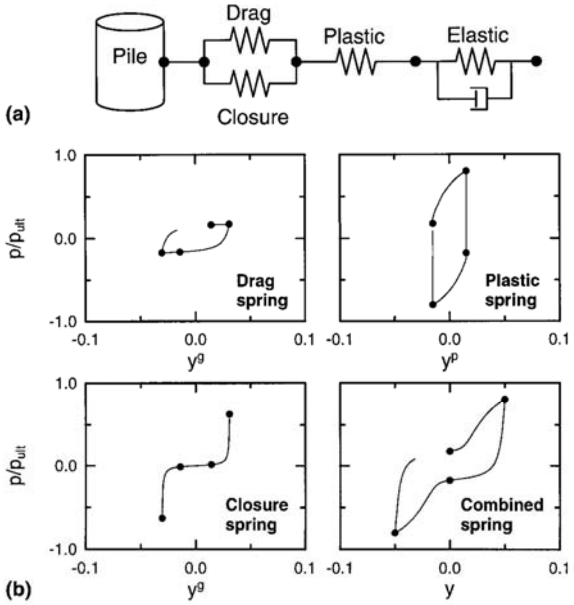


Fig. 1. Characteristics of Nonlinear p-y Element:(a) Components; (b) Behavior of Component

Also the damping component of the soil resistance is represented by a dashpot whose coefficient is established based on the Berger et al [14] model, i.e.,

$$C_L = 4B\rho v_s \tag{1}$$

Where $B$ = pile diameter, $v_s$ = soil shear wave velocity and $\rho$=soil unit density.

## 4. FREE FIELD EXCITATIONS

Free field ground motion time histories are usually computed using common site response analysis techniques. In site response analysis, the ground motion of the soil layer is calculated due to earthquake excitations applied at bedrock. The results of such free field analysis (acceleration or displacement time history at different soil layer) are then used as the input excitation at support nodes of the BNWF-Fiber Element model. [15]

In the present study the nonlinear stress-strain response of soil layers approximated by a nonlinear approach. In the analyses, Iwan [16] and Morz [17] model is used on which the nonlinear and hysteretic stress-strain behavior of soil is approximated by tangential shear modulus. A computer program NERA (Nonlinear Earthquake site Response Analysis) developed by Bardet et al [6] is used for free field ground motion analysis.

The lowstrain shear modulus $G_{max}$ was calculated from the dimensionless form of the equations by Seed and Idriss [18]:

$$\frac{G_{max}}{P_{atm}} = 21.8K_{2,max}\sqrt{\frac{\sigma'_m}{P_{atm}}} \qquad \text{for Sand}$$

$$K_{2,max} = 65 \quad \sigma'_m = (1+2K_0)\sigma'_{vc}/3 \quad K_0 = 0.6,\ P_{atm} = \text{atmospheric pressure} \tag{2}$$

$$\frac{G_{max}}{c_u} = 380 \qquad \text{for Clay} \tag{3}$$

## 5. MODEL AND GROUND MOTION RECORDS

Two structural models in this paper are 3D models and similar but one of them is with SSPSI and other is with equivalent dummy piles (without SSPSI). The provided model is formed by an assembling of frame elements in the nodes in general coordination system. This selected jacket type offshore has 141.7 m height. The platform is a six-leg jacket type which is installed in a water depth of 47.6 m. The jacket is located between -47.6 m and +7.25 m relative to L.A.T and the top side is located between +9 m and +24 m with three stories. In plan, the jacket is rectangular, 36m by 36m that is shown in figure 2. The elevations of jacket are shown in figure 3.

The platform has a three-stories topside with total mass of about 10000 tons located in center of each story and a four story jacket with total mass about 2000 tons located in main nodes of jacket. The platforms has different geometries in x and y directions. To accommodate platform heavy topside installation using float-over system, there are not any braces in sea water level bay in direction y and a portal action is formed in this direction.
The first natural period of platform is T1=3.03 sec. The members are modeled using a beam-column element. All analyses were performed using OPENSEES.

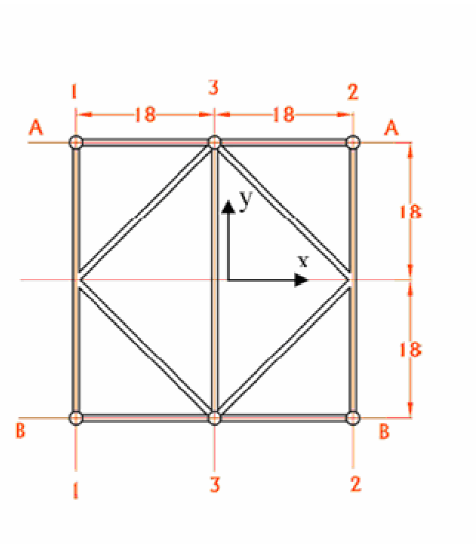


Figure 2. The jacket in plan

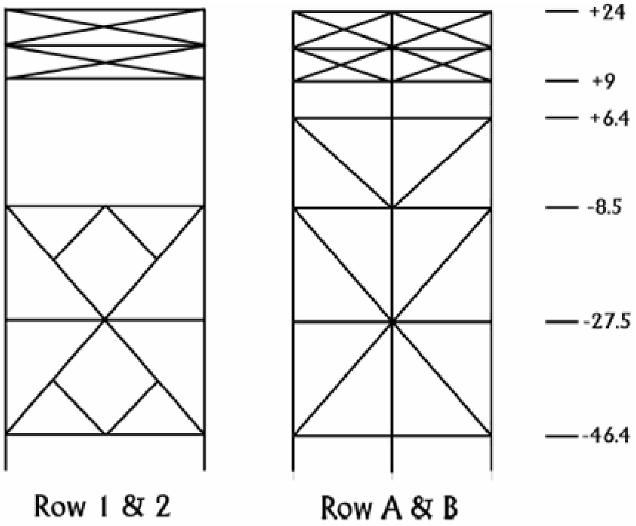


Figure 3. Elevation of offshore

For the modeling of SSPSI model, some nodes are introduced on pile with the same coordinate of main layer and sub-layer nodes. These two points have the same coordinates on the general coordinates. Based on the conditions of the cave-in and break in interaction between soil and pile, the interactive elements are introduced in the model. In this model, the relative movements of the nodes between pile and soil would be possible. In clay soil a gap is formed in tension stress situation. So the interactive element in the model should separate the node between pile and soil. For non-sticky soil, when the loading process is completed, the gap which is formed due to the non-sticky material would be filled. In BNWF nonlinear model, apart from modeling the pile in dynamic forces, the gapping and cave-in are modeled. For the modeling of structural steel, a bilinear elasto-plastic model with kinematic and isotropic hardening materials is suitable. The selected model for this study is an elasto-plastic model with strain hardening of 5 %.

For modeling of jacket, deck and pile members, the fiber elements have been used. By using this model, the buckling behavior and post buckling behavior of the tubular braces can be controlled by adding geometric stiffness [5]. As accuracy in P-delta analysis is suitable for the application in Earthquake engineering, it is used for applying the effects of decreasing the stiffness and strength.

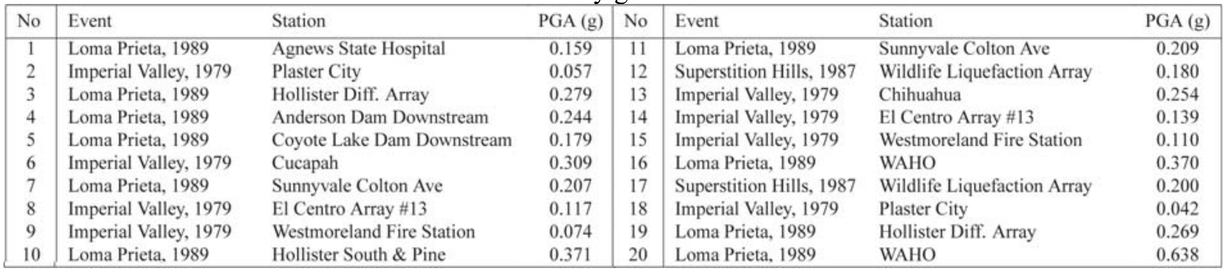
According to API (RP-2A) [13], in this essay, the mass used in the dynamic analysis consist of the mass of the platform associated with gravity loading, the mass of the fluids enclosed with the structure and the appurtenances, and the hydrodynamic added mass. The added mass may be estimated as the mass of the displaced water for motion transverse to the longitudinal axis of the individual structural framing and appurtenances. In computing the dynamic characteristics of braced, pile supported steel structures, viscous damping ratios of 5% are used for an elastic analysis.

In the SSPSI model, for soil dynamic analysis, the soil characteristics, layers and selected record are introduced in "NERA". Then by using "NERA", the time history of relative displacement at a selected sublayer is attained. After the formation of model, the time history of relative displacement of soil (in NERA) in pile nodes is applied and later the structure is analyzed by a nonlinear dynamic analysis [8].

The second model of jacket was created with above mentions and eliminating soil-pile-structure and modeling pile with equivalent dummy piles (pile stub). The length of pile stub was considered 15 times of pile diameter.

A set of twenty ground motion records is selected as listed in Table 1, that belong to a bin of relatively large magnitudes of 6.5 - 6.9 and moderate distances, all recorded on firm soil and bearing no marks of directivity.

Table 1. The suite of twenty ground motion records used.



| No | Event | Station | PGA (g) | No | Event | Station | PGA (g) |
|---|---|---|---|---|---|---|---|
| 1 | Loma Prieta, 1989 | Agnews State Hospital | 0.159 | 11 | Loma Prieta, 1989 | Sunnyvale Colton Ave | 0.209 |
| 2 | Imperial Valley, 1979 | Plaster City | 0.057 | 12 | Superstition Hills, 1987 | Wildlife Liquefaction Array | 0.180 |
| 3 | Loma Prieta, 1989 | Hollister Diff. Array | 0.279 | 13 | Imperial Valley, 1979 | Chihuahua | 0.254 |
| 4 | Loma Prieta, 1989 | Anderson Dam Downstream | 0.244 | 14 | Imperial Valley, 1979 | El Centro Array #13 | 0.139 |
| 5 | Loma Prieta, 1989 | Coyote Lake Dam Downstream | 0.179 | 15 | Imperial Valley, 1979 | Westmoreland Fire Station | 0.110 |
| 6 | Imperial Valley, 1979 | Cucapah | 0.309 | 16 | Loma Prieta, 1989 | WAHO | 0.370 |
| 7 | Loma Prieta, 1989 | Sunnyvale Colton Ave | 0.207 | 17 | Superstition Hills, 1987 | Wildlife Liquefaction Array | 0.200 |
| 8 | Imperial Valley, 1979 | El Centro Array #13 | 0.117 | 18 | Imperial Valley, 1979 | Plaster City | 0.042 |
| 9 | Imperial Valley, 1979 | Westmoreland Fire Station | 0.074 | 19 | Loma Prieta, 1989 | Hollister Diff. Array | 0.269 |
| 10 | Loma Prieta, 1989 | Hollister South & Pine | 0.371 | 20 | Loma Prieta, 1989 | WAHO | 0.638 |

## 6. PERFORMING THE ANALYSIS AND IDA CURVES

Once the model has been formed and the ground motion records have been selected, a way to perform the actual nonlinear dynamic analyses required for IDA is needed. This entails appropriately scaling each record to cover the entire range of structural response, from elasticity, to yielding, and finally global dynamic instability. [3] To use a stepping [8] algorithm to trace the IDA curves of platform is chose. Analyses are performed at increasing levels of IM at constant steps, until numerical non-convergence is encountered [4].

An IDA Curve set is a collection of IDA curves of the same structural model under different accelerograms that are all parameterized on the same IMs and DM [8]. Figures 4 to 5 shows all twenty IDA curves in x and y direction for two models.

By generating the IDA curve for each record a large amount of data can be gathered, only part. There, the IDA curves display a wide range of behavior, showing large record-to-record variability, thus making it essential to summarize such data and quantify the randomness introduced by the records. [4] They can be easily summarized into some central value (e.g., the mean or the median) and a measure of dispersion (e.g., the standard deviation, or the difference between two fractiles). Consequently, to calculate the 16%, 50% and 84% fractile values of DM and IM capacity is chosen, as shown in Figures 6 and 7.

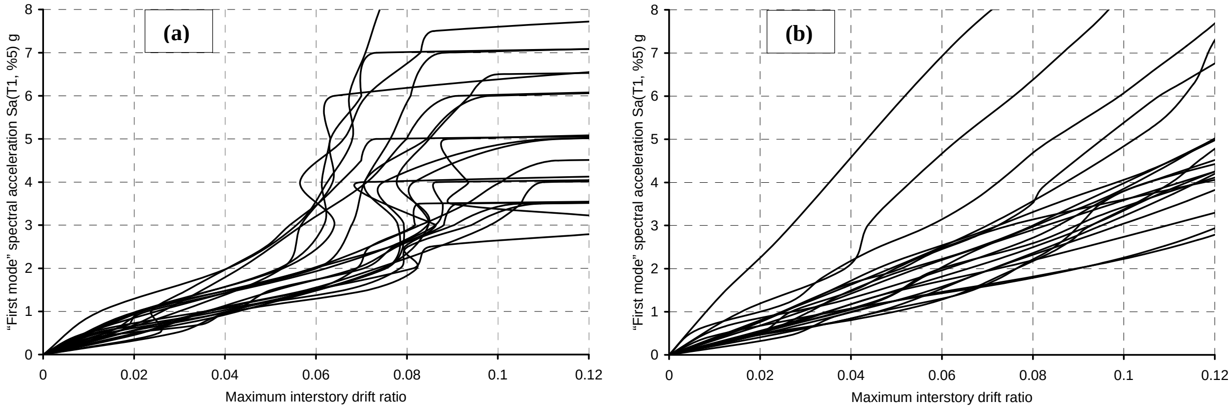


Figure 4. All twenty IDA curves in X direction of Jacket platform
(a) With considering Soil-Pile-Structure Interaction (b) without considering Soil-Pile-Structure Interaction

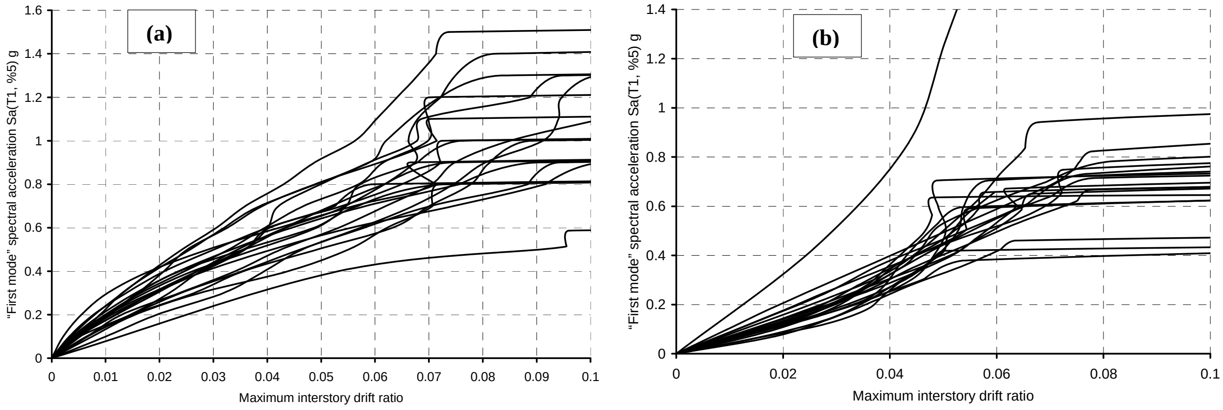


Figure 5. All twenty IDA curves in Y direction of Jacket platform
(a) With considering Soil-Pile-Structure Interaction (b) without considering Soil-Pile-Structure Interaction.

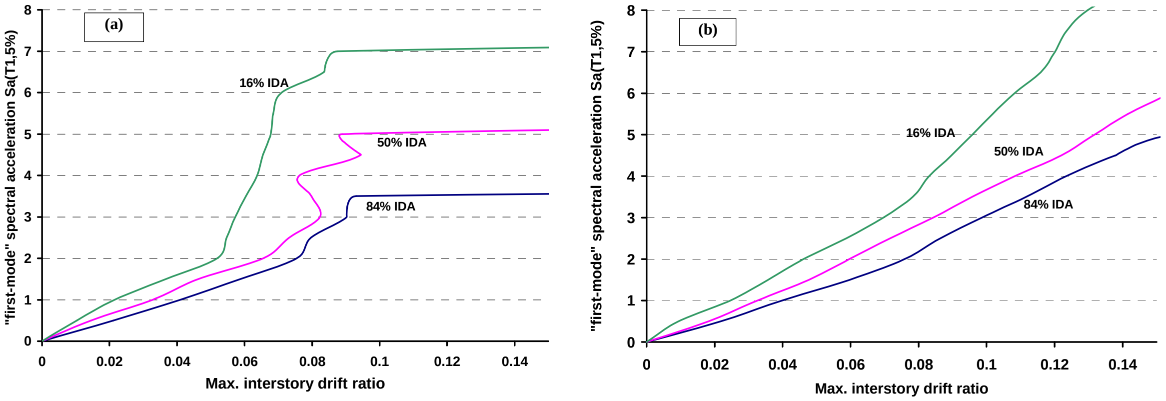


Figure 6. The summery of IDA curves in X direction of Jacket platform
(a) With considering Soil-Pile-Structure Interaction (b) without considering Soil-Pile-Structure Interaction.

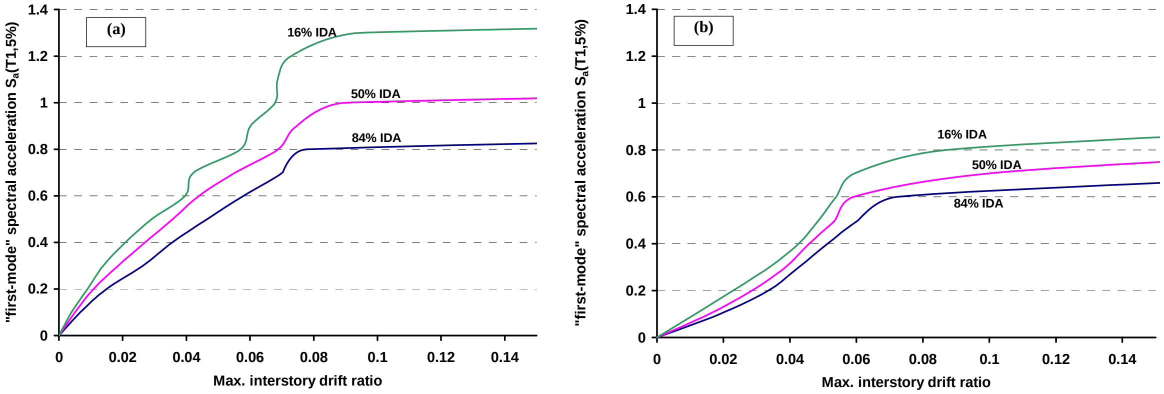


Figure 7. The summery of IDA curves in Y direction of Jacket platform
(a) With considering Soil-Pile-Structure Interaction (b) without considering Soil-Pile-Structure Interaction.

## 7.CONCLUSION

SSPSI is a fundamental subject in evaluation of offshore platforms behavior. In order to the figures in each direction before 0.06 drift ratio, behavior of the each models in both direction is almost similar. But after that depended to frames and interstory stiffness, behavior of the models in each direction is different. As in X direction that frames have more stiffness, flatline in model without SSPISI is upper than SSSPSI model. In this direction the model without SSPSI has almost linear behavior.

In Y direction because of conditions of deck installation with float-over method and less frames stiffness, flatline in model without SSPSI is lower than SSPSI model.

Difference of the model behavior with SSPSI and without SSPSI is depended to equivalent pile stiffness (length), frames stiffness and interstories stiffness. So nonlinear behavior of pile and surrounding soil plays an important role in actual behavior of a jacket in nonlinear range of deformation.

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