INCREMENTAL DYNAMIC ANALYSIS OF SHEET PILE QUAY-WALLS IN ORDER TO REACH PERFORMANCE-BASED DESIGN CRITERIA FOR THIS TYPE OF WHARF

Reza Dezvareh [1,*], Prof. Khosrow Bargi[2] & Yasin Moradi[3]
[1, 3] Ph.D Student, School of Civil Engineering, College of Engineering, University of Tehran, Iran
[2] Professor, School of Civil Engineering, College of Engineering, University of Tehran, Iran

ABSTRACT
Recent marine structure design codes i.e. PIANC and OCDI suggest performance based design (PBD) of various marine structures including quays. As well, current study concerns modern dynamic analysis technique of Sheet Pile Quay-walls, hoping for its contribution to assessment of quay performance criteria. Current study began with modeling of a conventional sheet pile quay-wall followed by dynamic analysis concerning soil-structure interaction and assessing the IDA curves and summarizing the results and in the end, Mean annual frequency (MAF) investigated.

Keywords: *Sheet pile quay walls, incremental dynamic analysis, Soil-Structure interaction, IDA curves*

1. INTRODUCTION
Quays are of essential parts of each port. Among all types, Sheet Pile Quay-walls are of major importance. Along with the development of marine transportations through Iranian long sea borders in north and south of the country, usage of modern design techniques are inevitable. Due to the high seismic vulnerability of the country, this paper tries to present author's new dynamic design achievements for Sheet Pile Quay-walls.
Recent marine structure design codes i.e. Pianc [1] and OCDI [2] suggest performance based design (PBD) of various marine structures including quays. As well, current study concerns modern dynamic analysis technique of Sheet Pile Quay-walls, hoping for its contribution to assessment of quay performance criteria.
Incremental Dynamic Analysis (IDA) is an advanced nonlinear dynamic analysis method that has absorbed much attention in the design of steel frames. It involves monitoring structural response from elastic to limit state through scaling ground motions. One of the most important applications of this method is assessing structure's behavior and design criteria in Performance-Based Earthquake Engineering (PBEE).
Current study began with modeling of a conventional sheet pile quay-wall followed by dynamic analysis concerning soil-structure interaction and assessing the IDA curves and summarizing the results and in the end, Mean annual frequency (MAF) investigated.

2. ABOUT INCREMENTAL DYNAMIC ANALYSIS
In this method, the model is exposed to one or several ground motions of different levels for each; structure's response curve is plotted. IDA curve of a structure is a curve for which an Intensity Measure (IM) like platform drift or maximum understory drift ratio is plotted versus damage measure (DM) or peak ground acceleration (PGA) or spectrum acceleration of first mode with 5% of damping. Limit-states and probability of exceeding a specified state can then be assessed through summarization of the obtained curves.

3. SEISMIC DESIGN FEATURES OF MARINE STRUCTURES CODE
Overseas Coastal Area Development Institute of Japan (OCDI) [2] is one of the most conventional codes for the design of Sheet Pile Quay-walls. It suggest to main earthquake levels for the design of quays:

- **3.1.** EQ hazard level 1: occurrence probability in service life of structure is about 20 to 50 percent (equal to an earthquake with the return period of 75 years), during which all modules of the port will continue their performance in elastic state.
- **3.2.** EQ hazard level 2: occurrence probability in service life of structure is about 10 to 20 percent (equal to an earthquake with the return period of hundreds of years), during which all modules of the port shall meet sufficient energy absorption in massive shakings.

4. PROBLEM DESCRIPTION AND MODELING
4.1. Sheet Pile Quay-wall
The length of the studied quay was 20.0 meter while its penetration depth was 10.0 meters. As installation of joint vertical piles is very formal, they were accordingly modeled in this study.

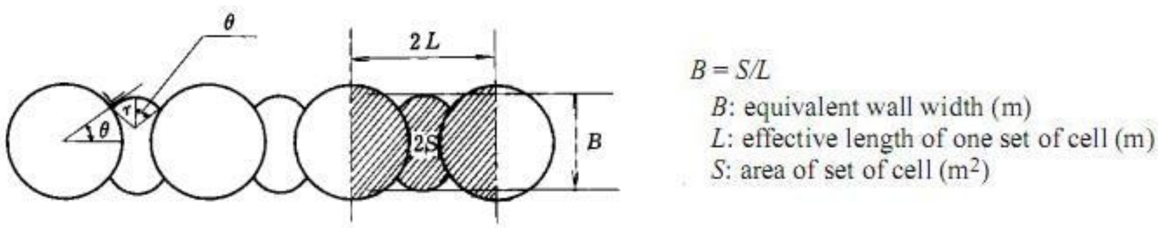

Figure 1. Section of sheet pile quay-wall

4.2. Soil Model and its Interaction with the Quay

Similar to other footing types, soil-structure interaction plays an important role in the analysis of marine structures. This role gets especially significant when concerning uplift capacity, overturning and slide of the structure. Nevertheless, soil body is the source of different forces imposed to the structure.

For this part of finite element analysis (FEM), soil was modeled using solid elements. Moreover, frictional properties and internal constrains of different parts were applied. Friction between soil and structures' elements were modeled by Penalty method.[3]

4.3. Material Properties

Material properties include concrete, steel and soil which were applied to platform, steel quay and soil, consequently.

- Concrete properties: Elasticity modulus of 2.08e7 kPa, Poison's ratio of 0.3 and unit weight of 2400 kg/m3
- Steel properties (St-52):Elasticity modulus of 2.07e8 kPa, Poison's ratio of 0.3 and unit weight of 7850 kg/m3
- Soil properties:

Table 1. Soil properties

	unit weight	**Yung's modulus**	**Pisson's ratio**	**Permeability**	**Cohesion**	**Internal friction angle**
	kg/m3	E_0	ν	k	C	φ
Sand	19.5	25	0.25	0.8e-5	0	36
Clay	19.5	25	0.25	0.8e-6	25	0

4.4. Introduction Finite Element Software and Loading

Capable of modeling various soil and structural elements and interactions, ABAQUS [4] has been used for the finite element dynamic analysis in this study. According to the table, ten different records were used for dynamic analysis, each of which were first scaled in NERA [5] and then applied to bed rock. The resultant soil response was finally applied to corresponding nodes.

Table 2. Properties of 10 used records

No	**Event**	**Station**	**PGA (g)**
1	Imperial Valley, 1979	Plaster City	0.042
2	Loma Prieta, 1989	WAHO	0.37
3	Superstition Hills, 1987	Wildlife Array	0.18
4	Imperial Valley, 1979	El Centro Array	0.117
5	Loma Prieta, 1989	Coyote Lake Dam	0.179
6	Superstition Hills, 1987	Wildlife Array	0.2
7	Imperial Valley, 1979	Westmoreland Fire Station	0.11
8	Loma Prieta, 1989	Sunnyvale Colton Ave	0.207
9	Superstition Hills, 1987	Hollister Diff. Array	0.269
10	Imperial Valley, 1979	Chihuahua	0.254

4.5. Boundary Conditions

Reflecting the energy waves by boundaries makes geotechnical models far from reality. To meet this phenomenon, absorbing boundaries were introduced to the model. The so called absorbing boundaries have been defined by Lymser&Kuhlmeyer (1969). Damping coefficient of elements C_d used in this analysis was calculated as:

$$C_d = \rho V_s A \quad (1)$$

- ρ: special gravity of soil
- V_s : Shear wave velocity
- A: Covered area of each element

5. RESULTS OF INCREMENTAL DYNAMIC ANALYSIS (IDA)

Following figures present the results of incremental dynamic analysis for two types of constrained (with lateral support) and cantilever (with no lateral support) sheet pile quay wall.

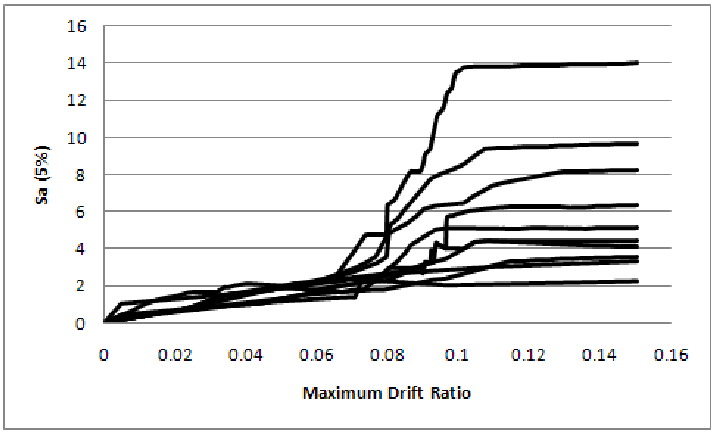

Figure 2. IDA Curves for constrained (lateral support) sheet pile

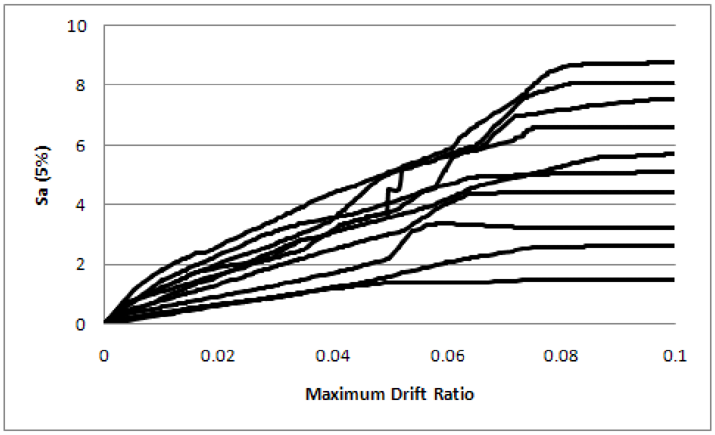

Figure 3. IDA Curves for cantilever (with no lateral support) sheet pile

6. INTRODUCTION LIMIT STATES FOR SHEET PILE

According to OCDI [2], there are two performance levels for port structures including quays that can be assessed through the following limit state:

- **Immediate Occupancy (IO):** It's a state limit during which post earthquake structural damages are limited and; lateral and vertically loaded elements still have their pre-quake stiffness and strength.
- **Collapse Prevention (CP):** This is the state in which structures undergoes sever damages that take it toward thorough collapse; elements have lost their pre-quake stiffnesses and large deformations are found.

Before using IDA curves, limit states shall be defined. For that, according to IDA curves categories and FEMA [6] code, three points of immediate occupancy (IO), Collapse Prevention (CP) and global dynamic instability (GI) are to be identified.

In this study, IO point was selected to be $\theta_{max} = 1\%$, while CP was either $\theta_{max} = 10\%$, or where IDA curve's slope is 20% of elastic portion, whatever comes sooner.
Thus, CP is assumed to be where IDA is on the pre straight line ductile area provided that θ_{max} is high enough and the structural model is reliable ($\theta_{max} < 1\%$). Finally, GI is where the curve becomes a straight line and every increment of intensity measure (IM) will result in infinite damage measure (DM). [7]

7. SUMMARIZATION OF IDA CURVES

For a better understanding of structure's behavior, IDA curves were summarized based on statistical principles. This paper uses 50, 16 and 84 percentages for summarizing. Figures 4 and 5 show the results of summarizing of IDA curves besides limit states for the two types of constrained and cantilever sheet pile quay walls. Numerical results can also be found in tables 2 and 3.
One of the other goals of performance based earthquake engineering (PBEE) is calculation of mean annual frequency (MAF) for the limit state. This can be easily done through summarization of the so far obtained results. For that, during this study, a particular integral limit state presented by Cornell [8] was used:

$$\lambda_{LS} = \int_{x=0}^{x=\infty} F_{IM}(x) \left| \frac{d\lambda_{IM}}{dx} \right| dx \qquad (2)$$

In the above relatios, λ_{LS} is the MAF corresponding to the limit state or the absolute of IM's risk gradient or first derivative of λ_{LS} - IM risk curve.

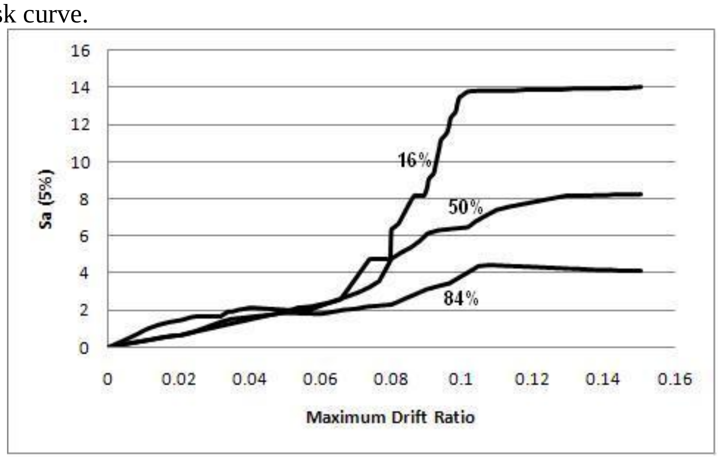

Figure 4. Summarization of IDA curves in the percentages of 16, 50 and 84 for constrained sheet pile

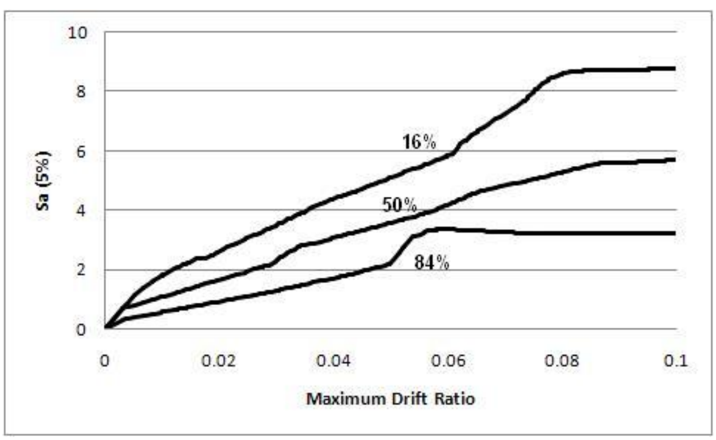

Figure 5. Summarization of IDA curves in the percentages of 16, 50 and 84 for cantilever sheet pile

The reverse of λ_{LS} will give the mean time for exceeding a specified state. Different amounts of MAF for various limit states of the constrained quay can be found in table 3 while those of the cantilever one are presented in table 4.

Table 3. Exceeding MAF's and the corresponding return period for the calculated limit state in the constrained sheet pile quay-wall

	IO	CP	GI
MAF	0.00875	0.00089	0.00051
Return Period (year)	114	1124	1961

Table 4. Exceeding MAF's and the corresponding return period for the calculated limit state in the cantilever sheet pile quay-wall

	IO	CP	GI
MAF	0.01075	0.00203	0.00151
Return Period (year)	93	493	662

8. CONCLUSIONS

According to OCDI, marine structures must be designed for strength level with return period of 100 to 200 years and deformability level with return period of 1000 to 2000 years. Results of incremental dynamic analysis on a sheet pile quay wall for two cantilever and constrained cases shows that the constrained case shall meet the required conditions while the cantilever one will fail to meet the requirements. Obviously the cantilever model will show weak dynamic behavior due to the lack of constrains and this must be taken into account in every analysis.

9. REFERENCES

[1]. PIANC (2001), Seismic Design Guidelines for Port Structures

[2]. The Overseas Coastal Area Development Institute of Japan (OCDI) (2002), Technical Standards and Commentaries for Port and Harbor Facilities in Japan

[3]. Boulanger RW, Curras CJ, Kutter BL, Wilson DW, Abghari A. (1999) "Seismic soil pile structure interaction experiments and analysis". Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 125(9), 750-759.

[4]. Abaqus Manual, ABAQUS/CAE 6.10-1, Dassault Systems Simulia Corp, Providence, RI, USA, 2010

[5]. Bardet, JP, Tobita T. (2001). "NERA- a computer program for Nonlinear Earthquake site Response Analysis of Layered Soil Deposits" . Department of Civil Engineering, University of Southern California.

[6]. FEMA. (2000) "Recommended seismic design criteria for new steel moment-frame buildings". Report No. FEMA-350, SAC Joint Venture, Federal Emergency Management Agency, Washington DC.

[7]. Vamvatsikos D, Jalayer F, Cornell CA. (2003) "Application of Incremental Dynamic Analysis to an RC-structure". Proceedings of the FIB Symposium on Concrete Structures in Seismic Regions, Athens.

[8]. Shome N, Cornell CA. (1999) "Probabilistic seismic demand analysis of nonlinear structures". Report No. RMS-35, RMS Program, Stanford University, Stanford.