Presenting Performance-Based Design Criteria of Pile and Deck Structures According to Seismic Design Guideline for Port Structure (PIANC)

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Abstract

In recent decade, considerable efforts, endeavors and researches have been made subject to review of dominant criteria and code on structures seismic Design that all of which focus mainly on structure behavior and operation in earthquake. These efforts causes for presenting new philosophy in design known as "performance-based design".

Seismic Design Guideline for port structure (PIANC) is the first instruction performance based design on operation. One of the main discussions in this design method is presenting design criteria in different performance level for evaluation of structures. Quality and quantity criteria such as deformation, stress and ductility are including criteria that named in this book. In technological literature, other criteria including relative deformation, permanent relative deformation, damages and energy index also are including in this part.

In this article, we want to analysis and design number of common pile and deck structure with use of seismic design guideline for port structure (PLANC). In this regard, structure seismic behavior and extent of incurred damages were taken into consideration and named criteria including energy index, damage index, length of plastic hinge, permanent deformation and ductility in different stages were analysis and designed. Results showed that there is opportunity for compilation of performance criteria for design of pile and deck structures.

Key words: Seismic design, Pile and deck structure, Performance based design, Seismic design guideline for port structure (PLANC).

Introduction

The occurrence of a large earthquake near a major city may be a rare event, but its societal and economic impact can be so devastating that it is a matter of national interest.

In order to mitigate hazards and losses due to earthquakes, seismic design methodologies have been developed and implemented in design practice in many regions since the early twentieth century, often in the form of codes and standards. Most of these methodologies are based on a force-balance approach, in which structures are designed to resist a prescribed level of seismic force specified as a fraction of gravity. These methodologies have contributed to the acceptable seismic performance of port structures, particularly when the earthquake motions are more or less within the prescribed design level. Earthquake disasters, however, have continued to occur. The limitations inherent in conventional design cause for presenting new philosophy in design known as "performance-based design".

Performance-Based Methodology

Performance-based design is an emerging methodology, which was born from the lessons learned from earthquakes in the ۱۹۹۰s. The goal is to overcome the limitations present in conventional seismic design. Conventional building code seismic design is based on providing capacity to resist a design seismic force, but it does not provide information on the performance of the structure when the limit of the force-balance is exceeded. If we demand that limit equilibrium not be exceeded in conventional design for the relatively high intensity ground motions associated with a very rare seismic event, the construction/retrofitting cost will most likely be too high. If force-balance design is based on a more frequent seismic event, then it is difficult to estimate the seismic performance of the structure when subjected to ground motions that are greater than those used in design.

In performance-based design, appropriate levels of design earthquake motions must be defined and corresponding acceptable levels of structural damage must be clearly identified. In performance-based design, the acceptable level of damage, i.e. damage criteria, should be specified in engineering terms such as displacements, limit stress state, and ductility/strain limit based on the function and seismic response of the structure.

Design philosophy of seismic design guideline for port structure (PIANC)

The evidence of damage to port structures suggests that:

- most damage to port structures is often associated with significant deformation of a soft or liquefiable soil deposit; hence, if the potential for liquefaction exists, implementing appropriate remediation measures against liquefaction may be an effective approach to attaining significantly improved seismic performance of port structures;
- most failure of port structures, from a practical perspective, result from excessive deformation, not catastrophic collapses; hence, design methods based on displacements and ultimate stress are desirable over conventional force-based design methods for defining the comprehensive seismic performance of port structures; and
- most damage to port structures is the result of soil-structure interaction; hence, design and analysis procedure should include both geotechnical and structural condition of port structures.

Evolving design philosophies for port structures in many seismically active regions reflect the observations that:

- deformation in ground and foundation soils and the corresponding structural deformation and stress state arte key design parameters;
- conventional limit equilibrium-based methods are not well suited to evaluating these parameters; and
- some residual deformation may be acceptable.

The performance-based methodology presented in this book incorporates these design philosophy into practice-oriented guidelines, and provides engineers with new tools for designing ports.

The principle steps taken in performance-based design are shown in the flowchart in Fig.١.

Two levels of earthquake motions are typically used as design reference motion, defined as follows:

Level ١ (L١): the level of earthquake motion that are likely to occur during the life-span of the structure. Level ١ earthquake motion is typically defined as motion with a probability of exceedance of ٥٠٪ during the life-span of the structure;

Level ٢ (L٢): the level of earthquake motions associated with infrequent rare events, which typically involve very strong ground shaking. Level ٢ earthquake motion is typically defined as motion with a probability of exceedance of ١٠٪ during the life-span. In defining these motions, near field motion from a rare event on an active seismic fault should also be considered.

Acceptable level of structural and operational damage, Performance grade S, A, B and C, and analysis methods for port structures given in Table.١, Table.٢ and Table.٣.

Table.١. Acceptable level of damage in performance-based design.

Level of damage	Structural	Operational
Degree I: Serviceable	Minor or no damage	Little or no loss of serviceability
Degree I: Repairable	Controlled damage	Short-term loss of serviceability
Degree I: Near collapse	Extensive damage in near collapse	Long-term or complete loss of serviceability
Degree I: Collapse	Complete loss of structure	Complete loss of serviceability

Fig.١. Flowchart for seismic performance evaluation.

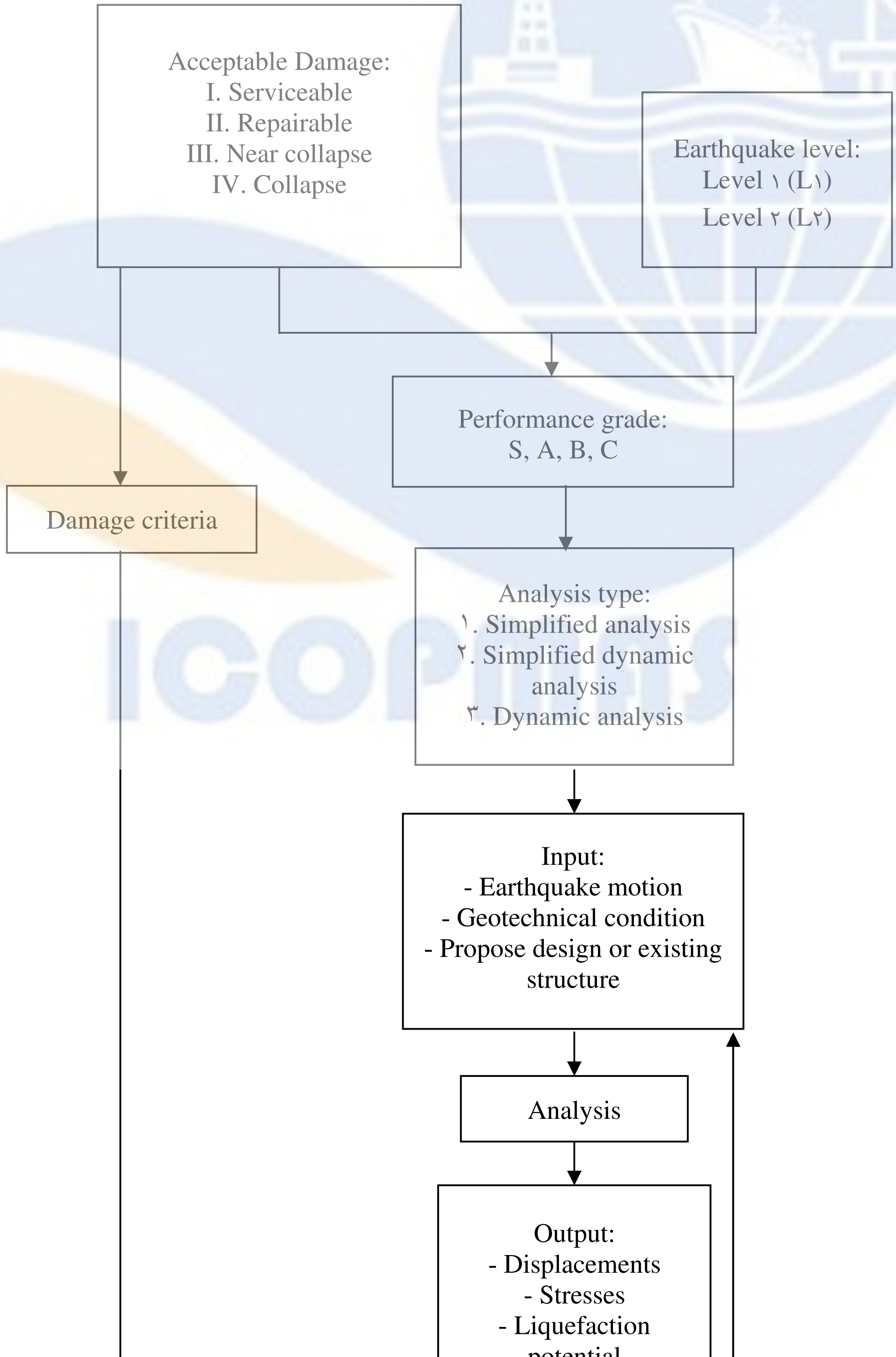

Table.٢. Performance grades S, A, B, and C.

Performance grade	Design earthquake	
	Level ١ (L١)	Level ٢ (L٢)
Grade S	Degree I: Serviceable	Degree I: Serviceable
Grade A	Degree I: Serviceable	Degree II: Repairable
Grade B	Degree I: Serviceable	Degree III: Near collapse
Grade C	Degree II: Repairable	Degree IV: Collapse

Table.٣. Analysis methods for port structures.

Type of analysis	Simplified analysis	Simplified dynamic analysis	Dynamic analysis	
			Structural modeling	Geotechnical modeling
Gravity quay wall	Empirical/pseudo-static methods with/without soil liquefaction	Newmark type analysis	FEM/FDM* Linear or Non-linear analysis ٢D/٣D**	FEM/FDM* Linear (Equivalent linear) or Non-linear analysis ٢D/٣D**
Sheet pile quay wall				
Pile-supported wharf	Response spectrum method	Pushover and response spectrum method		
Cellular quay	Pseudo-static analysis	Newmark type analysis		
Crane	Response spectrum method	Pushover and response spectrum method		
Break water	Pseudo-static analysis	Newmark type analysis		

* FEM/FDM: Finite Element Method/Finite Difference Method
**٢D/٣D: Two/Three-dimensional analysis.

Provided the condition mentioned at the beginning of this chapter are applicable, criteria for the piles and deck of a pile-supported wharf may be established by referring to Table.٤. The most restrictive condition among displacements and stresses should define the damage criteria.

Table.٤. proposed damage criteria for pile-supported wharves.

Level of damage		Degree I	Degree II	Degree III	Degree IV
Residual displacement	Differential settlement between deck and land behind	Less than ٠,١ m – ٠,٣ m	N/A*	N/A	N/A
	Residual titling towards the sea	Less than ٢ – ٣°	N/A	N/A	N/A
Peak response	Piles**	Essentially elastic response with minor or no residual deformation	Controlled limited inelastic ductile response and residual deformation intending to keep the structure repairable	Ductile response near collapse (double plastic hinges may occur at only one or limited number of piles)	Beyond the state of Degree III

* Abbreviation for not applicable.

**Bending failure should precede shear failure in structural components.

Characteristics of proposed pile –supported wharf

A pile-supported wharf with a water depth of ١٢ m was proposed for construction. The proposed cross section and plan of the pile-supported wharf shown in Fig.٢. Geotechnical parameters, including the coefficient of subgrade reaction, were determined from a geotechnical investigation and are given in Table.٥. The wharf supported by four rows of ١,٢ m diameter steel pipe piles. Piles in rows ١ through ٣ have a wall thickness of ١٢ mm, and the piles in row ٤ have a wall thickness of ١٤ mm. Structural parameters for these piles are given in Table.٦. Loads considered in the design include a ٣٠ kN/m^{٢} dead weight of the deck, and crane loads of ٢٤٠٠ kN per unit frame work of the pile-deck system. Structure was loaded on two different surcharges. Surcharge no. ١ was ١٠ kN/m^{٢} and other surcharge i.e. surcharge no. ٢ was ٣٠ kN/m^{٢}.

Fig.٢. proposed pile-supported wharf

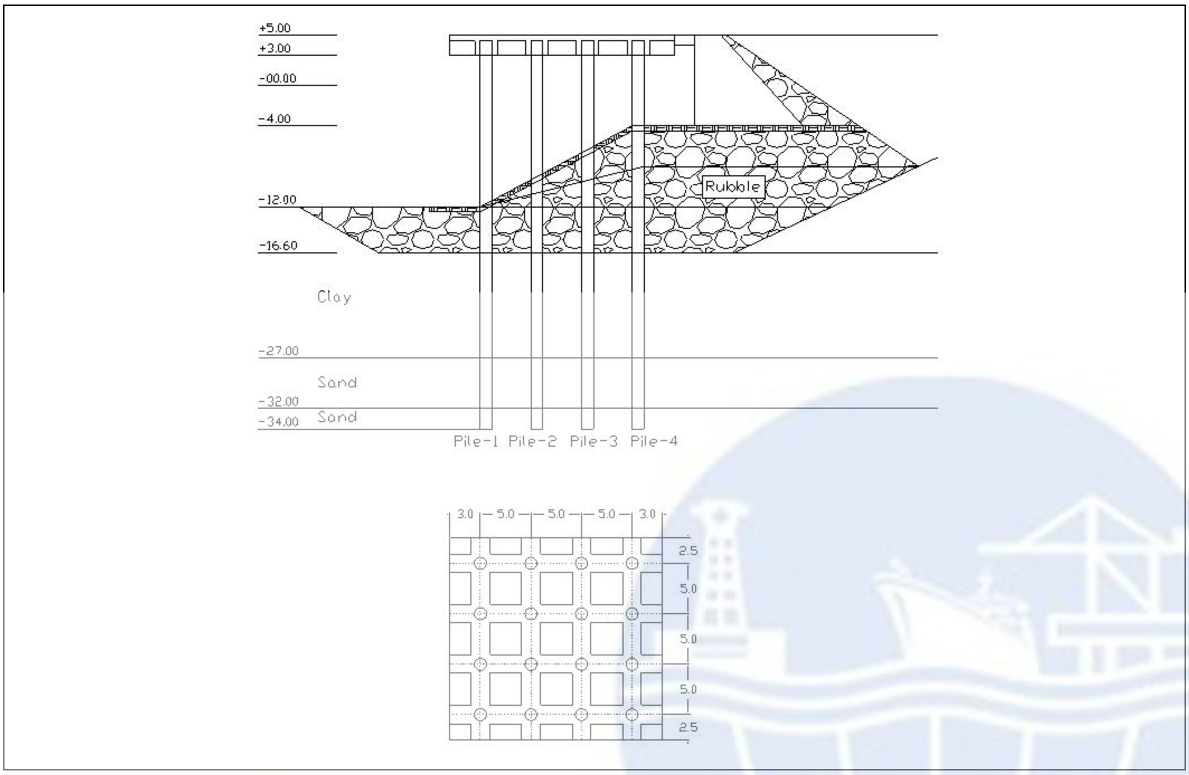

Table.٥. Major geotechnical parameters for pile-supported wharf.

Soil layers	Density (t/m^{٣})	Coefficient of subgrade reaction (kN/m^{٣})	Internal friction angle or unconfined compressive strength (kN/m^{٣})
Rubble	١,٩	٢٩٠٠٠	Φ=٣٠°
Soil layer ١ (Clay)	١,٦	٢٩٠٠٠	q_u=٦٠
Soil layer ٢ (Sand)	٢,٠	١١٧٠٠٠	Φ=٣٥°
Soil layer ٣ (Sand)	٢,٠	٢٩٠٠٠٠	Φ=٣٥°

Table.٦. Major pile parameters.

Type of parameter	Pile parameters	
	Piles ١ through ٣	Pile ٤
Diameter (m)	١,٢	١,٢
Thickness (m)*	٠,٠١١	٠,٠١٣
Cross section area (m^{٢})	٠,٠٤١٠	٠,٠٤٨٤
Moment of inertia (m^{٤})	٠,٠٠٧٢٣	٠,٠٠٨٥٠
Elastic section modulus (m^{٣})	٠,٠١٢٠	٠,٠١٤٢
Yield stress (kN/m^{٢})**	٣١٥٠٠٠	٣١٥٠٠٠
Yong modulus (kN/m^{٢})	٢,٠٦*١٠^{٨}	٢,٠٦*١٠^{٨}
* Cross section area and moment of inertia are computed by allowing loss of cross section in ١ mm thickness due to correction		
** Steel used was SKK٤٩٠ in JIS-A-٥٥٢٥		

The unit framework considered for design is indicated by hatching in Fig.٢. Soil-structure interaction was modeled by P-Y curve (Matlock. ١٩٧٠). Lateral load was applied two types: monotonic and cyclic load.

Models were labeled with both alphabet and number that shown type of applied surcharge and type of applied lateral load:

Marker number of applied surcharge,

١=Surcharge equals ١٠ kN/m^{٢}.
٢=Surcharge equals ٣٠ kN/m^{٢}.
Marker word of type of lateral load,
SC=Cyclic lateral load.
SM=Monotonic lateral load.

Model of studying pile-supported wharf

The computer program ANSYS٦،١ was used for the analysis. This program has different ability such as static analysis, time history analysis, modal analysis, spectrum analysis and other analysis. In addition, this program could model nonlinear behavior of material, creep, contact mechanism and other ability.

In this modeling, piles element was modeled with SHELL ١٨١ element and for springs modeling that were derived base on P-Y curve were used CONBINE ٣٩ element. Because the deck of structure was rigid, all nodes of piles those were located in top of piles constraint to one point. The inplan rotation of this point was limited. In all model, more over the springs were located in respective nodes, vertical movement of all nodes of piles that were located in bottom of piles were limited. In fact bottom of piles behavior such as roller supports.

Steel stress-strain curve assume with hardness equal ٢٪ elastic module. Lateral load was applied in two types: monotonic and cyclic load. In cyclic lateral load, load was increase ٢٠ mm in any time step. In this case, total displacement was ٣٢٠ mm. In other type of lateral load i.e. monotonic lateral load, load was increase ٤ mm in any time step. Total lateral displacement was ٥٠٠ mm. Lateral displacements in any type of lateral loads were applied to top of deck. In any time step, with applied lateral displacement could earn applied lateral load in supports and created strain and stress in piles elements.

Performance-based design criteria

In performance-based methodology chapter, some of performance-based design criteria were introduced. As regards to pile-supported wharf modeling, quantity results of design criteria was earn.

a) Displacement ductility factor:

Displacement ductility is maximum displacement of structure to elastic displacement of structure ratio. Elastic displacement is treatment of structure that more than half top of piles element reach to plastic range. Damage criteria were determined for the pile-deck structure only by damage degree I and III (Table.٤). Concerning major pile parameters, elastic strain was equal ٠،٠٠١٥٣. Displacement ductility factor of structures shown in Table.٧.

Table.٧. Displacement ductility factor of structures for different performance levels

Performance levels		Degree I	Degree II[١]	Degree III	Degree IV
Displacement ductility	١SM	١	١،٣٢	١،٦٤	----
	٢SM	١	١،٢٨	١،٥٥	----
	١SC	١	١،٣٣	١،٦٧	----
	٢SC	١	١،٢٨	١،٥٥	----

١. Amount of this performance level chose average of degree I and degree III

b) Permanent displacement:

Permanent displacements calculate with below formula. Results of models shown in Table.٨.

$dr = (\mu-١)\ dy$

Where

dr: Permanent displacement

dy: Elastic displacement

μ: Displacement ductility factor

Certainly, non-dimensional design criteria are better than dimensional design criteria for designing and comparing models. So, permanent displacement to elastic displacement ratio shown in Table.٩.

Table.٨. Permanent displacement for different performance levels.

Performance levels		Degree I	Degree II[١]	Degree III	Degree IV
Permanent displacement (mm)	١SM	----	٥٨	١١٦	----
	٢SM	----	٤٨	٩٦	----
	١SC	----	٥٤	١٠٨	----
	٢SC	----	٤٥	٩١	----

١. Amount of this performance level chose average of degree I and degree III

Table.٩. Permanent displacement to elastic displacement ratio for different performance levels.

Performance levels		Degree I	Degree II[١]	Degree III	Degree IV
Permanent displacement to elastic displacement ratio	١SM	----	٠,٣٢	٠,٦٤	----
	٢SM	----	٠,٢٧	٠,٥٥	----
	١SC	----	٠,٣٠	٠,٦٠	----
	٢SC	----	٠,٢٥	٠,٥١	----

١. Amount of this performance level chose average of degree I and degree III

c) Length of plastic hinge:

Plastic strain must be developed in critical element acceptably until length of plastic hinge could be evaluated correctly. So, length of plastic hinge was equal length of critical element that strain was reached at least double of elastic strain. Summery of result shown in Table.١٠.

Table.٧. Length of plastic hinge for different performance levels

Performance levels		Degree I	Degree II	Degree III				Degree IV
				Pile ١	Pile ٢	Pile ٣	Pile ٤	
Length of plastic hinges (cm)	١SM	----	----	٨٠	٣٠	٥	١٥	----
	٢SM	----	----	٥٠	----	----	----	----
	١SC	----	----	٢٢١	٢١٠	٢٠٣	١٩٠	----
	٢SC	----	----	٢١٧	٢٠٨	١٩٧	١٧٨	----

d) Energy index:

Energy index is hysterics energy or area of blew force-displacement curve to elastic energy ratio. Energy index was shown ability of energy absorption. Incidentally this index commend only for structures that applied cyclic lateral load. Energy index for different performance levels given in Table.١١.

Table.١١. Energy index for different performance levels

Performance levels		Degree I	Degree II`	Degree III	Degree IV
Energy index	١SC	١,٢٧	----	٤,٩٤	----
	٢SC	١,٨	----	٤,٩٨	----

e) Damage index:

Recent investigations show arisen distributions of structure element in earthquake motions that decreasing stiffness in any cycle of applied load, bounds of nonlinear behavior and volume of permanent stiffness is important. So, damage index was suggested by some researcher. This criteia calculate with below formula.

$$\omega = \frac{1}{H'_{max} U_{y1}} \sum_i E_i \left(\frac{K_i}{K_y}\right)\left(\frac{\Delta U_i}{U_{y1}}\right)^2$$

E_i = Hysterics energy in any cycle of applied load
K_i = Mean stiffness in any cycle of applied load
$U_{y١}$= Elastic displacement elements
K_y = elastic stiffness i.e. elastic modulus elements
H_{max} = Maximum applied lateral load
ΔU_i = Mean displacement in any cycle of applied load

As mention earlier, damage index communicate energy index directly. Damage index for different performance levels given in Table.١١.

Table.١١. Damage index for different performance levels

Performance levels		Degree I	Degree II`	Degree III	Degree IV
Energy index	١SC	١,٧٩	----	٨,٨	----
	٢SC	١,٩٨	----	٧,٩٤	----

Reference

١. Seismic Design Guideline for Port Structure, Working Group NO.٣٤ of the Maritime Navigation Commission, International Navigation Association, ٢٠٠٠.
٢. Technical Standard for Port and Harbour Facilities in Japan, Ministry Of Transport, Japan ٢٠٠٢.
٣. Applied Technology Council (ATC), ١٩٩٦, Seismic Evaluation and Retrofit of Concrete Buildings, vol.١, ATC٤٠, Redwood City, CA.
٤. Bertero, V. V., ١٩٩٧, Performance-Based Seismic Engineering: A Critical review of proposed guidelines, In: Seismic Design Methodologies for the Next Generation of Codes, Proceeding of the International Workshop on Seismic Design Methodologies for the Next Generation of Codes, Balkema, Rotterdam, P. ١-٣١.
٥. Fajfar, p., EERI, M., ٢٠٠٠, A Nonlinear Analysis Method for Performance-Based Seismic Design, Earthquake Spectra, Vol. ١٦, NO.٣, August ٢٠٠٠, P.٥٧٣-٥٩٢
٦. FEMA ٢٧٣, ١٩٩٦, NEHRP Guideline for the Seismic Rehabilitation of buildings, Ballot version, Federal Emergency Management Agency.
٧. SEOAC, ١٩٩٥, Performance Based Seismic Engineering of Building, Vol.١,April ١٩٩٥.
٨. Kramer, S.L, ١٩٩٦, Geotechnical Earthquake Engineering, Prentice Hall, ٦٥٣ p.

۹. Iai, S. & Ichii, K. ۱۹۹۸, Performance Based Design for Port Structures, Proc. UJNR ۳۰th Joint Meeting of United States-Japan Panel on Wind and Seismic Effect, Gaithersburg, NIST (۳-۵), pp. ۱-۱۳

۱۰. Collins, K, R. Stojadinovic, B., Limit State Performance-Based Design, ۱۲th World Conference on Earthquake Engineering Auckland, New Zealand, ۲۰۰۰.

۱۱. Iai Susumu Seismic Performance-Based Design of Port Structures and Simulation Techniques, Port and Airport Research Institute.