Seismic Performance-Based Design of Port Structures and Simulation Techniques

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Abstract

The paper presents highlights of the seismic design guidelines for port structures developed by the International Navigation Association (PIANC). The author served as chairman of a working group for developing the guidelines. The members of the working group represent 11 countries, including Algeria, Canada, Denmark, Germany, Greece, Italy, Japan, Netherlands, Spain, UK, and USA. The guidelines are the first of their kind in presenting international guidelines for seismic design. The provisions reflect the diverse nature of port facilities: constructed along a long waterfront line, they provide multiple land-sea alternative transport connections (e.g., one failed berth during an earthquake can be compensated by nearby operational berths); facilities are provided for small to very large vessels, and critical facilities, including those for handling potentially hazardous materials and those which must be emergency operational immediately after a devastating earthquake.

The primary charge of the working group was to develop a consistent set of seismic design guidelines that would have broad international support. The characteristics of port structures mentioned earlier led the working group to adopt an evolutionary design strategy based on seismic response and performance requirements of port structures. Proven simplified methods and state-of-the-art analysis procedures have been carefully chosen and integrated in the guidelines in order to provide a flexible and consistent methodology for the seismic design of port facilities.

Future international collaborative activities following the publication of the guidelines include (1) systematic comparison of the analysis procedures presented in the guidelines, and (2) implementation of the guidelines in practice around the world. Interested parties are welcome to get in touch with the author.
Introduction

Although the damaging effects of earthquakes have been known for centuries, it is only since the mid-twentieth century that seismic provisions for port structures have been adopted in design practice. In 1997, the International Navigation Association (PIANC) set up a working group, PIANC/MarCom/WG34, to focus international attention on the devastating effects of earthquakes on port facilities in the late twentieth century around the world. The members of the working group represent 11 countries, including Algeria, Canada, Denmark, Germany, Greece, Italy, Japan, Netherlands, Spain, UK, and USA, with the author being the chairman. A book, entitled “Seismic Design Guidelines for Port Structures,” is the culmination of the efforts of this working group (PIANC, 2001). This paper presents highlights of the guidelines.

International Guidelines

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This book consists of a main text and eight technical commentaries. The main text introduces the reader to basic earthquake engineering knowledge and a strategy for seismic performance-based design. The technical commentaries illustrate specific aspects of seismic analysis and design, and provide examples of various applications of the guidelines.

Seismic Response of Port Structures

In conventional design philosophy, structures must remain stable against wave, wind and earthquake loads. The main focus has been on the evaluation and identification of the threshold level, below which structures remain stable and do not move. Recent earthquakes in the 1990’s around the world strongly suggest that we have to turn our attention beyond the threshold level.
Performance of structures, including mode of deformation/failure and extent of damage, becomes a major issue for design consideration. Earthquake damage and deformation/failure modes for typical port structures are summarized below.

**Gravity Quay Walls**
A gravity quay wall is made of a caisson or other rigid wall put on the seabed, and maintains its stability through friction at the bottom of the wall. Typical failure modes during earthquakes involve seaward displacement, settlement and tilt. For a quay wall constructed on a firm foundation, an increase in earth pressure from the backfill plus the effect of an inertia force on the body of the wall result in the seaward movement of the wall as shown in Fig. 1(a). If the width to height ratio of the wall is small, tilt may also be involved. Case histories for gravity quay walls subjected to earthquake shaking often belong to this category. When the subsoil below the gravity wall is loose and excess pore water pressure increases in the subsoil, however, the movement of the wall is associated with significant deformation in the foundation soil, resulting in a large seaward movement involving tilt and settlement as shown in Fig. 1(b). The latter mode of failure has received wide attention since the Kobe, Japan, earthquake of 1995.

![Fig. 1 Deformation/failure modes of gravity quay walls](image)

**Anchored Sheet Pile Walls**
An anchored sheet pile wall is composed of a wall, anchors and tie-rods. Each structural component contributes to the stability of the whole structure. In the ultimate state of stability, it should be decided, out the wall of the anchor, which should be the first to yield. Excessive displacements of the anchor are undesirable. A small movement of the anchor, however, contributes to reducing the tension in the tie-rods and the bending moment in the wall. Well-balanced response of the wall and anchor is essential for ascertaining the reasonable
A variety of geotechnical conditions can result in a variety of failure modes of an anchored sheet pile wall. In particular, three failure modes may be identified depending on the extent of loose, saturated sandy soils relative to the position and geometry of the wall. If the deformation of a loose deposit mainly affects the stability of anchors as shown in Fig. 2(a), the anchors will move toward the sea, resulting in the seaward movement of the wall. This mode of deformation/failure has been the most frequently observed at waterfronts. If the deformation of the loose deposit mainly affects the backfill of the wall as shown in Fig. 2(b), the earth pressure increase will cause an excessively large bending moment in the wall, resulting in yielding of the wall. This mode of failure has also been observed during past earthquakes.

If the deformation of the loose sandy deposit mainly affects the stability of the embedment portion of the wall as shown in Fig. 2(c), a gross instability of the wall at the embedment portion should exist. This mode of failure, however, can occur only when the anchor is strong and firmly embedded, and both the wall and tie-rods are very strong. In current design practice, the wall is assumed to be relatively firmly embedded, and, thus, is designed for a fraction of the bending moment induced at the free-earth support conditions. If the conditions shown in Fig. 2(c) are met, yielding of the wall or failure of the anchor will most likely precede the instability of the embedment portion. This may be the reason why there has not been a case history that fits the failure mode shown in Fig. 2(c).

Fig. 2 Deformation/failure modes of sheet pile quay walls
Pile Supported Wharf
A pile supported wharf is composed of a deck supported by a substructure consisting of piles and a dike, often simply called a wharf. Because the dike is sloped, the piles between the deck and the dike will have various unsupported lengths. Three causes of failure may be identified for a pile supported wharf. For a wharf constructed on a firm foundation having a rigid and stable dike, the seismic inertia force on the deck will be the main cause of failure as shown Fig. 3(a). The maximum bending moment occurs at the row of pile heads most landward because these piles have the shortest unsupported length. If there is an excessively large displacement at the top of the dike or the retaining structures, the deck will be pushed seaward, resulting in a similar mode of failure as shown in Fig. 3(b). For a wharf constructed on a loose foundation, the displacement in the dike will directly push the piles seaward as shown in Fig. 3(c). The first cause of failure has been well taken into account in conventional seismic design of pile supported wharves. Increasing attention has been directed toward the effect of displacement of dikes on a pile supported wharves since the Loma Prieta, USA, earthquake of 1989. The Kobe, Japan, earthquake of 1995 again demonstrated the importance of this.

Fig. 3 Deformation/failure modes of pile supported wharves
Seismic Performance-Based Design

Performance-based design is an emerging methodology, which was born from the lessons learned from earthquakes in the 1990’s. 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 a 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. Two levels of earthquake motions are typically used as design reference motions, defined as follows:

- **Level 1 (L1):** the level of earthquake motions that are likely to occur during the life-span of the structure;
- **Level 2 (L2):** the level of earthquake motions associated with infrequent rare events, that typically involve very strong ground shaking.

The acceptable level of damage is specified according to the specific needs of the users/owners of the facilities and may be defined on the basis of the acceptable level of structural and operational damage given in Table 1. The structural damage category in this table is directly related to the amount of work needed to restore the full functional capacity of the structure and is often referred to as direct loss due to earthquakes. The operational damage category is related to the amount of work needed to restore full or partial serviceability. Economic losses associated with the loss of serviceability are often referred to as indirect losses. In addition to the fundamental functions of servicing sea transport, the functions of port structures may include protection of human life and property, functioning as an emergency base for transportation, and

<table>
<thead>
<tr>
<th>Acceptable level of damage</th>
<th>Structural</th>
<th>Operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree I: Serviceable</td>
<td>Minor or no damage</td>
<td>Little or no loss of serviceability</td>
</tr>
<tr>
<td>Degree II: Repairable</td>
<td>Controlled damage**</td>
<td>Short-term loss of serviceability***</td>
</tr>
<tr>
<td>Degree III: Near collapse</td>
<td>Extensive damage in near collapse</td>
<td>Long-term or complete loss of serviceability</td>
</tr>
<tr>
<td>Degree IV: Collapse****</td>
<td>Complete loss of structure</td>
<td>Complete loss of serviceability</td>
</tr>
</tbody>
</table>

* Considerations: Protection of human life and property, functions as an emergency base for transportation, and protection from spilling hazardous materials, if applicable, should be considered in defining the damage criteria in addition to those shown in this table.

** With limited inelastic response and/or residual deformation

*** Structure out of service for short to moderate time for repairs

**** Without significant effects on surroundings
as protection from spilling hazardous materials. If applicable, the effects on these issues should be considered in defining the acceptable level of damage in addition to those shown in Table 1.

Once the design earthquake levels and acceptable damage levels have been properly defined, the required performance of a structure may be specified by the appropriate performance grade S, A, B, or C defined in Table 2. In performance-based design, a structure is designed to meet these performance grades.

**Table 2 Performance grades S, A, B, and C**

<table>
<thead>
<tr>
<th>Performance grade</th>
<th>Design earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level 1(L1)</td>
</tr>
<tr>
<td>Grade S</td>
<td>Degree I: Serviceable</td>
</tr>
<tr>
<td>Grade A</td>
<td>Degree I: Serviceable</td>
</tr>
<tr>
<td>Grade B</td>
<td>Degree I: Serviceable</td>
</tr>
<tr>
<td>Grade C</td>
<td>Degree II: Repairable</td>
</tr>
</tbody>
</table>

The principal steps taken in performance-based design are shown in the flowchart in Fig. 4:

1) Choose a performance grade from S, A, B, or C: This step is typically done by referring to Tables 1 and 2 and selecting the damage level consistent with the needs of the users/owners. Another procedure for choosing a performance grade is to base the grade on the importance of the structure. Degrees of importance are defined in most seismic codes and standards. This procedure is presented in Table 3. If applicable, a performance grade other than those of S, A, B, or C may be introduced to meet specific needs of the users/owners.

2) Define damage criteria: Specify the level of acceptable damage in engineering parameters such as displacements, limit stress states, or ductility factors. The details are addressed in the guidelines (PIANC, 2001).

3) Evaluate seismic performance of a structure: Evaluation is typically done by comparing the response parameters from a seismic analysis of the structure with the damage criteria. If the results of the analysis do not meet the damage criteria, the proposed design or existing structure should be modified. Soil improvement including remediation measures against liquefaction may be necessary at this stage. Details of liquefaction remediation can be found in the publication of the Port and Harbour Research Institute, Japan (1997).
Acceptable damage:
I Serviceable
II Repairable
III Near Collapse
IV Collapse

Earthquake level:
Level 1 (L1)
Level 2 (L2)

Performance grade:
S, A, B, C

Analysis type:
1. Simplified analysis
2. Simplified dynamic analysis
3. Dynamic analysis

Input:
Earthquake motions
Geotechnical conditions
Initial design or existing structure

Analysis

Output:
Displacements
Stresses
(Liquefaction potential)

Are damage criteria satisfied?
Yes
End of performance evaluation

No
Modification of cross section/soil improvement

Fig. 4 Flowchart for seismic performance evaluation
Table 3 Performance grade based on the importance category of port structures

<table>
<thead>
<tr>
<th>Performance grade</th>
<th>Definition based on seismic effects on structures</th>
<th>Suggested importance category of port structures in Japanese code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade S</td>
<td>• Critical structures with potential for extensive loss of human life and property upon seismic damage</td>
<td>Special Class</td>
</tr>
<tr>
<td></td>
<td>• Key structures that are required serviceable for recovery from earthquake disaster</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Critical structures that handle hazardous materials</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Critical structures that, if disrupted, devastate economic and social activities in the earthquake damage area</td>
<td></td>
</tr>
<tr>
<td>Grade A</td>
<td>Primary structures having less serious effects for through• than Grade S structures, or</td>
<td>Special Class or Class A</td>
</tr>
<tr>
<td></td>
<td>• Structures that, if damaged, are difficult to restore.</td>
<td></td>
</tr>
<tr>
<td>Grade B</td>
<td>Ordinary structures other than those of Grades S, A and C.</td>
<td>Class A or B</td>
</tr>
<tr>
<td>Grade C</td>
<td>Small easily restorable structures.</td>
<td>Class B or C</td>
</tr>
</tbody>
</table>

Seismic Performance Evaluation/Analysis

The objective of analysis in performance-based design is to evaluate the seismic response of the port structure with respect to allowable limits (e.g. displacement, stress, ductility/strain). Higher capability in analysis is generally required for a higher performance grade facility. The selected analysis methods should reflect the analytical capability required in the seismic performance evaluation.

A variety of analysis methods are available for evaluating the local site effects, liquefaction potential and the seismic response of port structures. These analysis methods are broadly categorized based on a level of sophistication and capability as follows:

1) Simplified analysis: Appropriate for evaluating approximate threshold limit for displacements and/or elastic response limit and an order-of-magnitude estimate for permanent displacements due to seismic loading.

2) Simplified dynamic analysis: Possible to evaluate extent of displacement/stress/ductility/strain based on assumed failure modes.

3) Dynamic analysis: Possible to evaluate both failure modes and the extent of the displacement/stress/ductility/strain.

Table 4 shows the type of analysis that may be most appropriate for each performance grade. The principle applied here is that the structures of higher performance grade should be evaluated using more sophisticated methods. As shown in the index in Table 4, less sophisticated methods may be allowed for preliminary design, screening purpose, or response analysis for low levels of excitation.

The methods for analysis of port structures may be broadly classified into those applicable to retaining/earth structures, including quay walls, dikes/slopes and breakwaters, or those
applicable to open pile/frame structures, including pile/deck system of pile-supported wharves and cranes.

Table 4 Types of analysis related to performance grades

<table>
<thead>
<tr>
<th>Type of analysis</th>
<th>Performance grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grade C</td>
</tr>
<tr>
<td>Simplified analysis:</td>
<td></td>
</tr>
<tr>
<td>Appropriate for evaluating approximate threshold</td>
<td></td>
</tr>
<tr>
<td>level and/or elastic limit and order-of-magnitude</td>
<td></td>
</tr>
<tr>
<td>displacements.</td>
<td></td>
</tr>
<tr>
<td>Simplified dynamic analysis:</td>
<td></td>
</tr>
<tr>
<td>Of broader scope and more reliable. Possible to</td>
<td></td>
</tr>
<tr>
<td>evaluate extent of displacement/stress/ductility/strain</td>
<td></td>
</tr>
<tr>
<td>based on assumed failure modes.</td>
<td></td>
</tr>
<tr>
<td>Dynamic analysis:</td>
<td></td>
</tr>
<tr>
<td>Most sophisticated. Possible to evaluate both failure</td>
<td></td>
</tr>
<tr>
<td>modes and extent of displacement/stress/ductility/</td>
<td></td>
</tr>
<tr>
<td>strain.</td>
<td></td>
</tr>
</tbody>
</table>

Index:
- Standard/final design
- Preliminary design or low level of excitations

Methods for Analysis of Retaining/Earth Structures

Simplified Analysis
Simplified analysis of retaining/earth structures is based on the conventional force-balance approach, sometimes combined with statistical analyses of case history data. The methods in this category are often those adopted in conventional seismic design codes and standards. In simplified analysis, retaining/earth structures can be idealized as rigid blocks of soil and structural masses. The rigid block analysis is typically applied for gravity, sheet pile and cellular quay walls, dike/slope/retaining walls for pile-supported wharves and breakwaters.

Effects of earthquake motions in simplified analysis are represented by a peak ground acceleration or an equivalent seismic coefficient for use in conventional pseudo-static design procedures. These parameters are obtained from the simplified analysis of local site effects discussed in the previous section. A capacity to resist the seismic force is evaluated based on structural and geotechnical conditions, often in terms of a threshold acceleration or a threshold seismic coefficient, beyond which the rigid blocks of soil and structural masses begin to move. When soil liquefaction is an issue, the geometric extent of liquefaction must also be considered in the analysis.

Simplified Dynamic Analysis
Simplified dynamic analysis is similar to simplified analysis, idealizing a structure by a sliding rigid block. In simplified dynamic analysis, displacement of the sliding block is computed by
integrating the acceleration time history that exceeds the threshold limit for sliding over the
duration until the block ceases sliding.

Effects of earthquake motions are generally represented by a set of time histories of earthquake
motion at the base of a structure. The time histories of earthquake motion are obtained from the
simplified dynamic analysis of local site effects discussed in the previous section. In the sliding
block analysis, structural and geotechnical conditions are represented by a threshold acceleration
for sliding. A set of empirical equations obtained from a statistical summary of sliding block
analyses is available. In these equations, peak ground acceleration and velocity are used to
represent the effect of earthquake motion.

In more sophisticated analysis, structural and geotechnical conditions are idealized through a
series of parametric studies based on non-linear Finite Element Method (FEM)/Finite Difference
Method (FDM) analyses of soil-structure systems and the results are compiled as simplified
charts for use in evaluating approximate displacements.

**Dynamic Analysis**
Dynamic analysis is based on soil-structure interaction, generally using FEM or FDM methods.
In this category of analysis, effects of earthquake motions are represented by a set of time
histories of earthquake motion at the base of the analysis domain chosen for the soil-structure
system. A structure is idealized either as linear or as non-linear, depending on the level of
earthquake motion relative to the elastic limit of the structure. Soil is idealized either by
equivalent linear or by an effective stress model, depending on the expected strain level in the
soil deposit during the design earthquake.

Fairly comprehensive results are obtained from soil-structure interaction analysis, including
failure modes of the soil-structure system and the extent of the displacement/stress /strain states.
Since this category of analysis is often sensitive to a number of factors, it is especially desirable
to confirm the applicability by using a suitable case history or a suitable model test result.

**Analysis Methods for Pile/Frame Structures**

**Simplified Analysis**
Simplified analysis of open pile/frame structures is typically done by idealizing the pile/deck
system of pile-supported wharves or the frame of cranes by a single degree of freedom (SDOF)
or multi-degree of freedom (MDOF) system. In this analysis, earthquake motions are generally
represented by the response spectrum. Structural and geotechnical conditions are represented by
a resonant frequency and damping factor of the deck-pile system and/or the cranes. A ductility
factor may also be introduced. The movement of the dike/slope is generally assumed to be
negligible. Results of the SDOF/MDOF analysis are useful to evaluate approximate limit state
response of a pile-deck system or a crane.

**Simplified Dynamic Analysis**
In simplified dynamic analysis of open pile/frame structures, the SDOF or MDOF analysis of
pile-deck structure or cranes is combined with pushover analysis for evaluating the ductility
factor/strain limit. The movement of the dike/slope is often assumed to be negligible but
sometimes estimated by a sliding block type analysis. Movement of a pile-supported deck could
thereby be estimated by summing-up the dike/slope movement and structural deformation. Soil-structure interaction effects are not taken into account, and thus there is a limitation in this analysis. Interaction between the pile-supported wharves and cranes can be taken into account by MDOF analysis. Displacement, ductility factor/ strain, and location of yielding or buckling in the structure are generally obtained as a result of the analysis of this category. Failure modes with respect to sliding of retaining walls/dikes/slopes are not evaluated but assumed and there is, thus, another limitation in this type of analysis.

**Dynamic Analysis**
Dynamic analysis is based on soil-structure interaction, generally using FEM/ FDM methods. Similar comments to those related to the dynamic analysis of earth/retaining structures apply also to the open pile structures and cranes.

**Summary & Conclusions**

The PIANC seismic guidelines for port structures have been put together based on a new concept called performance-based design. This approach introduces into design an acceptable level of damage depending on the required performance of a structure. This approach should be the key to accomplishing higher reliability of a structure against earthquakes without appreciable increase in construction cost. Analytical techniques needed for the performance-based design are emerging and available. They are categorized in three levels of increasing sophistication. The PIANC seismic guidelines are a user-friendly approach, giving the users/engineers options to choose from and allowing us much flexibility in seismic design.

Future international collaborative activities following the publication of the guidelines include (1) systematic comparison of the analysis procedures presented in the guidelines, and (2) implementation of the guidelines in practice around the world. Interested parties are welcome to get in touch with the author.

**References**