A PERFORMANCE – BASED DESIGN APPROACH IN TURKISH SEISMIC DESIGN CODE FOR PORT STRUCTURES

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ABSTRACT:
A new seismic design code is being enforced in Turkey, effective September 1, 2008, for transportation structures officially administered by General Directorate for Construction of Railways, Harbors and Airports (RHA) of Ministry of Transportation. The aim of this contribution is to describe the main aspects of the RHA Seismic Code with special emphasis given to port structures. The most important aspect of the code rests on its main approach incorporating “performance-based design”. In this context, port structures have been classified with respect to their expected seismic performance, usage and functional importance, namely, special, nominal, simple and unimportant structures. This is followed by standard definition of performance levels, namely “Minimum Damage Performance Level”, “Controlled Damage Performance Level” and “Excessive Damage Performance Level” prior to state of collapse. On the other hand, design earthquakes have been specified in three levels with probability of exceedance of 50%, 10% and 2% in 50 years, respectively. Minimum performance objectives are then specified for each class of structure under different earthquake levels. Two different classes of design methods have been specified in the code, namely, Strength-Based Design (SBD) and Deformation-Based Design (DBD). The latter includes practice-oriented nonlinear analysis, namely pushover analysis as well as nonlinear response history analysis in the time domain. Acceptance criteria are specified in terms of nonlinear deformation quantities for multi-level performance objectives. In view of a very limited number of seismic codes available for port structures, the new Turkish Seismic Code is expected to attract a special attention with its modern approach.

KEYWORDS:
Port structures, seismic code, performance-based design, deformation-based design, performance objectives.

1. INTRODUCTION

Rapid development of international sea trade in the last few decades has eventually led to questioning of seismic safety of port structures. Heavy damage occurred in Port of Kobe in disastrous Kobe Earthquake of 1995 was a costly reminder to earthquake engineering community regarding the lack of modern seismic design guidelines and codes specifically addressed to port structures. In 2001, a notable attempt was made by International Navigation Association (formerly Permanent International Association for Navigation Congresses – PIANC) Working Group 34 through the publication of Seismic Design Guidelines for Port Structures (PIANC 2001). In the following years, first generation of modern seismic codes for port structures emerged from California, USA. In this respect, Port of Los Angeles seismic code (POLA 2004) and Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS 2005) are the most recent examples. The latter is based on extensive preparatory studies by Ferrito et al (1999).

The common design philosophy behind all the above-mentioned codes is the *performance-based design*. As opposed to traditionally used prescriptive *strength-based approach*, performance-based design rests on an explicit *deformation-based approach*, where damage is *quantified* in terms of inelastic deformation demand quantities on element level under specified multi-level earthquakes and such *ductile* demand quantities are then evaluated against prescribed *deformation capacities* for selected *performance objectives* under each earthquake level. In the mean time internal force quantities corresponding to *brittle* behavior modes are ensured not to exceed the specified *strength capacities*.

The General Directorate for Construction of Railways, Harbors and Airports (RHA) of Ministry of Transportation of Turkish Republic has commissioned a group of experts in 2005 for the preparation of a seismic code applicable to transportation structures officially administered by RHA. The aim of this contribution is to describe the main aspects of the RHA Seismic Code (Ministry of Transportation 2007) with a special emphasis given to port structures. The code, as a whole, rests completely on a performance-based design philosophy, as explained in this paper.

2. PERFORMANCE – BASED DESIGN PARAMETERS

As in any performance-based design code, the RHA code for port structures starts with the definition of the following performance-based design parameters:

(a) Structural classes associated with the expected performance, usage and functional importance,
(b) Seismic performance levels associated with expected damage levels,
(c) Earthquake levels associated with frequent, rare and very rare earthquakes,
(d) Seismic performance objectives under different earthquake levels.

The above-listed parameters are explained in the following paragraphs.

2.1. Structural Classes

Port structures are classified as special, nominal, simple and unimportant structures.

2.1.1. Special Structures

(a) Structures to be used for rapid response and evacuation immediately after an earthquake,
(b) Structures to be used for toxic, flammable or explosive materials.

2.1.2. Nominal Structures

(a) Structures where the loss of life and property must be avoided,
(b) Structures of economic and social significance,
(c) Structures with difficult and time-consuming post-earthquake repair and retrofit needs,

2.1.3. Simple Structures

(a) Less important structures other than those classified in Special and Nominal Structures,
(b) Structures other than those classified as Unimportant Structures.

2.1.4. Unimportant Structures

(a) Easily replaceable structures,
(b) Structures not causing life safety risk even extensively damaged,
(c) Temporary structures.

2.2. Seismic Performance Levels

Seismic performance levels of port structures are defined with respect to expected damages during an earthquake.

2.2.1. Minimum Damage (MD) Performance Level

This performance level corresponds to a state where no or a very limited damage occurs in port structures and/or in their elements under an earthquake. In this case, port operation continues uninterrupted or if any, service interruptions are limited to few days.

2.2.2. Controlled Damage (CD) Performance Level

This performance level corresponds to a state where non-extensive, repairable damage occurs in port structures and/or in their elements under an earthquake. In this case, short-term (few weeks or months) interruptions in related port operations may be expected.

2.2.3. Extensive Damage (ED) Performance Level

This performance level corresponds to a state where extensive damage occurs in port structures and/or in their elements under an earthquake. In this case, long-term interruptions or even closures in related port operations may be expected.

2.2.4. State of Collapse (CS)

This corresponds to the collapse state in port structures and/or in their elements under an earthquake. Related port operation is terminated.

2.3. Earthquake Levels

Three different levels of earthquakes are defined in terms of their intensity, representing frequent, rare and very rare seismic events. Response spectra ordinates of the relevant earthquakes are given for the entire country in an annex of the code.

2.3.1. (E1) Earthquake Level

This earthquake level represents relatively frequent but low-intensity earthquake ground motions with a high probability to occur during the service life of port structures. The probability of exceedance of (E1) level earthquake in 50 years is 50%, which corresponds to a return period of 72 years.

2.3.2. (E2) Earthquake Level

This earthquake level represents the infrequent and high-intensity earthquake ground motions with a low probability to occur during the service life of port structures. The probability of exceedance of (E2) level earthquake in 50 years is 10%, which corresponds to a return period of 475 years.

2.3.3. (E3) Earthquake Level

This earthquake level represents the highest intensity, very infrequent earthquake ground motions that port structures within the scope of the code may be subjected to. The probability of exceedance of (E3) level earthquake in 50 years is 2%, which corresponds to a return period of 2475 years.

2.4. Seismic Performance Objectives

Minimum performance objectives are specified for each class of port structure given in Section 2.1 under different earthquake levels defined in Section 2.3 as shown in Table 2.1.

Table 2.1 Minimum performance objectives for port structures

Structure Class	(E1) Earthq. Level	(E2) Earthq. Level	(E3) Earthq. Level
Special	–	MD	CD
Nominal	MD	CD	(ED)*
Simple	CD	(ED)*	–
Unimportant	(ED)*	(CS)*	–

* *Implied objectives* not requiring design verification.

3. ANALYSIS AND DESIGN PROCEDURES

Being a performance-based code, the new Turkish seismic code for port structures mainly rests on a *deformation-based design (DBD)* approach, which in turn requires the implementation of nonlinear seismic analysis procedures. However, linear analysis procedures within the framework of traditional *strength-based design (SBD)* are allowed for the verification of *Minimum Damage (MD) Performance Objective* where structural behavior is at or near the elastic limits. Linear procedures are further allowed for the verification of *Controlled Damage (CD) Performance Objective* with relatively conservative design parameters. Table 3.1 indicates the design approaches to be used for different classes of structures under multi-level earthquakes. The table should be read with Table 2.1 where the corresponding performance objectives are given.

Table 3.1 Applicable design approaches to port structures

Structure Class	(E1) Earthq. Level	(E2) Earthq. Level	(E3) Earthq. Level
Special	–	SBD / DBD	DBD
Nominal	SBD	SBD / DBD	–
Simple	SBD	–	–
Unimportant	–	–	–

In the following both *strength-based design* approach and *deformation-based design* approach are explained as implemented in the code with particular reference to pile supported wharves and piers.

3.1. Strength-based design approach for pile supported structures

In *strength-based design* (SBD) approach for piled systems, the structure is analyzed linearly under reduced seismic loads, as similar to the standard building seismic design codes. Seismic load reduction factor $R_a(T)$ is defined in terms of period of vibration, T, as

$$R_a(T) = 1.5 + (R - 1.5)\,\frac{T}{T_S} \qquad (0 \le T \le T_S)$$
$$R_a(T) = R \qquad (T_S < T) \tag{3.1}$$

where T_S represents the transition period of the response spectrum at the intersection of constant acceleration and constant velocity regions, and R is the structural behavior factor given in Table 3.2 for pile supported wharves and piers.

Table 3.2 Structural Behavior Factors (*R*)

Structure	Pile arrangement	Performance Level	
		MD	CD
Wharf	Vertical piles	1.5	2.5
	Batter piles	1.0	1.5
Pier	Vertical piles	2.5	4.0
	Batter piles	1.0	1.5

3.1.1. Inadequacy of strength-based design for batter piled structures.

Batter piles are commonly preferred in piers and wharves, in particular for their satisfactory performance under breasting and mooring loads. However, batter piled systems perform very poorly in earthquakes because of their inherent lack of ductility. In fact majority of strength-based designed batter piled piers and wharves have exhibited very poor performance in recent earthquakes, namely 1989 Loma Prieta earthquake and 1995 Kobe earthquake (Ferrito et al 1999, PIANC 2001), and 1999 Izmit earthquake in Turkey (Boulanger et al 2000). It is for this reason that the design and construction of batter piles are virtually prohibited in the current Californian code practice unless special measures are taken or specially designed structural fuse systems are used (POLA 2004, MOTEMS 2005).

As observed from Table 3.2, batter piled systems were assigned very low *R* factors in the new Turkish code, i.e., *R*=1 is specified for MD level and *R*=1.5 for CD level. Note that, as opposed to Californian practice, the intention of the code is not to avoid the use of batter piles completely. Instead, the designer is strongly discouraged to employ the strength-based approach and fictitious linear analysis under artificially reduced seismic loads to simulate highly complex nonlinear behavior of such systems in earthquakes. In fact, recently Harn (2004[a,b]) showed that the complex seismic behavior of batter piles can only be explained with nonlinear analysis, and advocated the use practical nonlinear analysis procedures for a rational seismic design of batter piled structures. The so-called *pole vaulting* phenomenon is shown to be the major source of failures in pile-to-deck connections and in deck elements.

Thus, by assigning very low values to *R* factors for batter piles, the new Turkish code effectively pushes the designer to use deformation-based design approach in batter piled systems with or without structural fuse systems (Harn 2004[b]), or otherwise to choose vertical pile systems for an efficient seismic design.

3.1.2. Analysis methods

For the linear analysis under reduced seismic loads, the Equivalent Seismic Load Method based on single-mode response as well as multi-mode Spectral Mode Combination Method have been specified in the code.

3.2. Deformation-based design approach

Deformation-Based Design (DBD) approach based on nonlinear analysis is essentially required for *nominal* and *special* class structures to verify the Controlled Damage (CD) performance objective. Recommended nonlinear analysis procedures include response-history analysis in the time domain as well as practice oriented nonlinear analysis procedures based on single-mode and multi-mode pushover analyses (Aydınoğlu 2003, 2004), which are recently included as well in the Turkish seismic design code for buildings (Ministry of Public Works and Settlement 2007). Traditional plastic hinge model as well as fiber models is recommended for nonlinear pile and pile-to-cap beam dowel connection modeling. In piled structures, soil is recommended to be modeled with nonlinear p-y, t-z and Q-z springs.

Regarding the plastic hinge at the pile-to-cap beam/deck *dowel connection*, the plastic hinge length, L_p , is specified as the sum of strain penetration lengths into the pile and cap beam or deck:

$$L_p = 0.044 f_y d_b \tag{3.2}$$

where f_y and d_b represent the yield strength and diameter of the dowel, respectively. In-ground plastic hinges are characterized with a plastic hinge length of twice the section depth.

Regarding the reinforced concrete dowel connection at the pile/pile cap interface, the yield surface of the section may be piecewise linearized and strain hardening effect may be neglected as shown in Fig.3.1. In constructing the yield surface of the connection, concrete compressive strain and dowel reinforcement tensile strength may be taken as 0.004 and 0.015, respectively (Priestley, 2003). The normality condition is to be considered for plastic deformation vector.

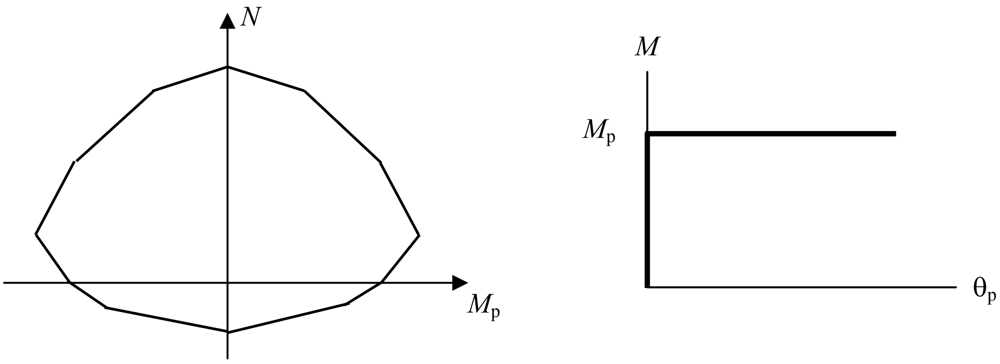

Figure 3.1. Linearized yield surface and elasto-plastic moment-plastic rotation relationship

3.2.1. Estimation of deformation demands

Inelastic deformation demands obtained from the nonlinear analysis are verified against the corresponding capacities given for various performance objectives, as explained in the following.

In pile supported piers and wharves, nonlinear deformation demands are obtained either directly in terms of strains (in fiber analysis) or in terms of plastic rotations through plastic hinge analysis. Since deformation capacities have been defined in the code in terms strains, any plastic rotation, θ_p , has to be converted first to plastic curvature, ϕ_p , through an appropriately defined plastic hinge length, L_p , followed by the calculation of total curvature, ϕ_t , by adding the yield curvature, ϕ_y (Fig.3.2).

$$\phi_p = \frac{\theta_p}{L_p} \quad ; \quad \phi_t = \phi_y + \phi_p \tag{3.3}$$

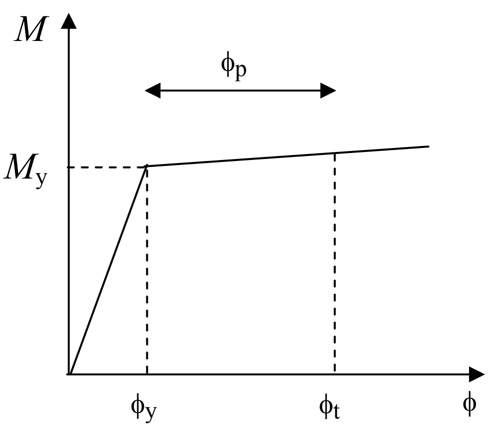

Figure 3.2. Bi-linearized moment-curvature relationship

Concrete and reinforcing steel strain demands in reinforced and prestressed concrete piles, and steel strain demands in steel piles are then estimated from the corresponding curvatures under prevailing axial force demands.

3.2.2. Acceptance criteria for damage limits: Strain capacities

The estimated strain demands as above, are checked against below given strain capacities, which correspond to accepted damage limits for a given seismic performance objective. The criteria basically follow those given in POLA (2004) and MOTEMS (2005).

Table 3.3 Strain capacities for piles

Strain	Performance Objective	
	MD	CD
Reinforced and prestressed concrete pile		
Plastic section at pile-to-pile cap/deck connection:		
Concrete compressive strain	0.005	0.020
Reinforcing steel tensile strain	0.010	0.040
Prestressed concrete pile		
In-ground plastic section:		
Prestressing steel strain	0.005(1)	0.040
Steel pipe pile		
Plastic section at reinforced concrete pile-to-pile cap/deck connection:		
Concrete compressive strain	0.008	0.025
Reinforcing steel tensile strain	0.010	0.040
Compressive or tensile steel strain at in-ground plastic section:		
Hollow steel pipe pile	0.008	0.025
Concrete infilled pipe pile	0.008	0.035
(1) Strain increment due to earthquake action		

3.2.3. Shear strength capacities

In addititon to specifying deformation capacities of ductile members, brittle force capacities, such as shear capacities, have been defined as well to compare with the shear demands in piles, pile-to-deck connections and deck elements.

4. CONCLUSIONS

General Directorate for Construction of Railways, Harbors and Airports (RHA) of Ministry of Transportation has recently issued a new seismic design code applicable to railways, harbor/port structures and airports in Turkey. In this paper, main aspects of the code are explained with particular reference to the seismic design requirements for port structures.

As its main feature, the code rests on a performance-based seismic design philosophy. In this context, classification of port structures, definition of damaged-based performance levels, multi-level earthquake actions and performance objectives are briefly described in the paper as the essential parameters of the performance-based design. Applicable analysis and design procedures are explained with a special emphasis given to the requirements of deformation-based nonlinear design of pile supported port structures.

In view of a very limited number of seismic codes available for port structures, the new Turkish Seismic Code is expected to attract a special attention with its modern approach.

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