New Bridge Seismic Isolation Design Specifications of Turkey

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ABSTRACT: Under the sponsorship of General Directorate of Highways of Turkey, a new specification is developed for the seismic isolation design of highway and railway bridges. This paper describes the distinct features of the newly developed seismic isolation bridge design specifications of Turkey in comparison to AASHTO Guide Specifications for Seismic Isolation Design of Bridges and EN15129: European Standard on Anti-Seismic Devices. The comparative study is performed for different sections of the design specifications including the parts related to; (i) the classification of bridges for analysis and design, (ii) seismicity and design response spectra, (iii) equivalent linear and time history analyses, (iv) types of seismic isolation and energy dissipation devices covered in design specifications, (v) design of seismic isolation and energy dissipation devices, and their minimum testing requirements and (vi) minimum requirements of seismic isolation and energy dissipation devices to ensure continued functionality and serviceability of the bridge. The comparative study revealed that the new Bridge Seismic Isolation Design Specifications of Turkey differs in many ways compared to AASHTO and EN15129 including the approaches related to the seismicity and design spectra with particular emphasis on near-field effects, minimum requirements for the serviceability of bridges, property modification factors used for seismic isolation and energy dissipation devices as well as testing procedures.

1 INTRODUCTION

Application of seismic isolation technology has seen a rapid increase in Turkey in recent years, particularly in case of buildings. Following the completion of Turkish national code for seismic design of buildings (TBDY 2018) in 2018 in which a chapter is devoted to seismically isolated buildings, General Directorate of Highways of Turkey, has launched an effort to develop similar specifications for the seismic design of highway and railway bridges and other lifeline structures and seismically isolated highway and railway bridges. This paper describes the distinct features of the newly developed seismic isolation bridge design specifications of Turkey, as part of the Turkish Bridge Design Standard (TBDS (2019)) in comparison to AASHTO Guide Specifications for Seismic Isolation Design of Bridges (AASHTO GSID 2014) and EN15129: European Standard on Anti-Seismic Devices. The above two documents have been consulted in development of the new standard, along with ASCE 7-16 and other well-known national codes for seismic isolation of bridges and buildings.

2 THE CLASSIFICATION OF BRIDGES FOR ANALYSIS AND DESIGN

Three distinct classification of bridges are considered in the Turkish Bridge Design Standard (TBDS (2019)). Based on typology, the bridges are categorized into two groups, namely,

1. Standard bridges
2. Special bridges

This categorization is intended to make a distinction between ordinary types of bridges and others such as cable-stayed, suspension, arch and truss bridges which are categorized as special bridges. Based on their usage, performance, and importance the standard bridges are categorized into three groups, namely,

1. Important bridges
2. Normal bridges
3. Other bridge

Bridges with strategic importance and those which are critical in transportation system or provide access to centres which are considered critical in emergency management are categorized as 'important bridges'. Single-span bridge and bridges with a maximum length of 100m, having a maximum of 3 spans and maximum pier height of 10, without any features in their structure which complicates their design, are categorized as 'other bridge'. All other bridges outside these two categories are categorized as 'normal bridges'. Based on the degree of complicacy in the analysis process, the bridges are categorized into three groups, namely,

1. Complex bridges
2. Single-span straight bridges
3. Other bridge

Where, those bridges with features which introduce complicacy in their analysis process are grouped as complex bridges. Such features include close proximity to an active fault (distance less than 25 km) large effective damping (≥30%) large-period bridges (≥1.0 sec) curved bridge is and bridges with large screw angle (>20º).

3 SEISMICITY AND DESIGN RESPONSE SPECTRA

The proposed design response spectrum in TBDS (2019) follows that of ASCE 7-16, both in form and the values proposed for site coefficients. The only difference is that in case of TBDS (2019) the maximum direction effect factor is not considered in preparation of the mapped spectral response acceleration parameters. Thus, the code proposes factors by which the mapped spectral response acceleration parameters should be multiplied, before using these parameters in the equations or to obtain side coefficient values. The proposed maximum direction factors are as follows. In case of bridges located at sites with shortest distance to the active fault more than 25 km (L_F≥25 km), δ_s=1.2 and δ_1=1.3 are amplifiers for short-period and long-period acceleration parameters, respectively. In case of bridges located at sites with shortest distance to the active fault less than 25 km (L_F<25 km), δ_s=1.2 is the amplifier for short-period acceleration parameter; and γ_F which is a factor to consider the near field effect is used to amplify the long-period acceleration parameters. γ_F is given by the following equations:

$$\gamma_F = 1.2 \qquad L_F \leq 15\ km \qquad (1)$$

$$\gamma_F = 1.2 - 0.02(L_F - 15) \quad 15km \leq L_F < 25\ km$$

The design response spectrum in TBDS (2019) is based on a 475-year return period earthquake. This is also the case in EN 1998-2. However, EN 1998-2 recognizes the use of an importance factor (γ_I) which can be as large as 1.3 for bridges with class III importance to allow for design for higher return period earthquake (lower-probability earthquakes). The value for γ_I is left to be determined by the national annex. There is no similar concept in TBDS (2019), however, the design displacement of the isolation system is amplified by two reliability factors as will be described in Section 6.1. AASHTO GSID (2014) bases the design on a 1000-year return period earthquake. However, the isolation system is required to have a displacement capacity of at least 1.1 times the total design displacement for the maximum considered earthquake. According to the commentary in AASHTO GSID (2014), in the absence of a site-specific hazard study the maximum considered earthquake may be taken as one with a 2500-year return period earthquake.

4 EQUIVALENT LINEAR AND TIME HISTORY ANALYSES

TBDS (2019) proposes two different damping reduction equations for the equivalent linear analysis, making a distinction between the far-field and near-field located bridges. The equation for far-field located bridges is identical to that of AASHTO GSID (2014):

$$B_s = (\xi_e / 0.05)^{0.30} \qquad (2)$$

In case of bridges located at sites with shortest distance to the active fault more than 25 km, the following equation is proposed, which is based on the research by Dicleli & Kara (in press):

$$B_s = 1 + 3[(\xi_e - 0.05)^{0.85}]\left[(\frac{\sum Q_d\ g}{0.4 S_{DS} W})^{0.25}\right]\left[(\frac{T_B}{T_d})^{0.40}\right] \qquad (3)$$

Where ξ_e denotes effective damping, g is gravitational acceleration, S_{DS} is the spectral acceleration response parameter at short period, W is the weight of the superstructure, T_B is the corner period at the end of velocity sensitive region of the design spectrum, T_d is the post-elastic period of the isolation system calculated based on the post-elastic stiffness, $\sum Q_d$ is the overall characteristic strength of the isolation system.

In the study by Dicleli & Kara (in press) a new damping reduction equation is proposed to obtain reasonable estimates of the actual nonlinear responses of seismic isolated structures subjected to near fault ground motions with forward-rupture-directivity effect, using equivalent linear analysis (ELA) procedure. A comparison between Equation (3 and those suggested by AASHTO GSID (2014) and

EN15129 is presented in bar charts in Figure 1. The charts show the ratio of displacements obtained from equivalent linear analysis using the relevant damping reduction equation to those obtained from nonlinear time history analysis.

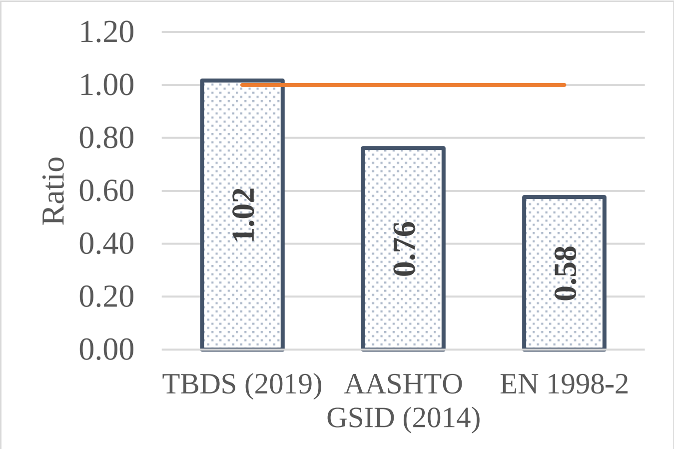

Figure 1. Ratio of displacements obtained from equivalent linear analysis using the relevant damping reduction equation to those obtained from nonlinear time history analysis.

5 TYPES OF SEISMIC ISOLATION AND ENERGY DISSIPATION DEVICES COVERED IN DESIGN SPECIFICATIONS

Types of seismic isolation and energy dissipation devices covered in TBDS (2019) include low and high-damping elastomeric bearings, lead-rubber bearings, flat and curved-surface sliders and metallic and viscous dampers. Specifically, the code recognizes double-surface friction pendulum isolators with unequal upper and lower surface friction coefficients, which require deployment of restraining ring in the upper or lower surface, as shown in Figure 2. The code also addresses metallic dampers with adaptive behaviour having a typical force-displacement curve, shown in Figure .

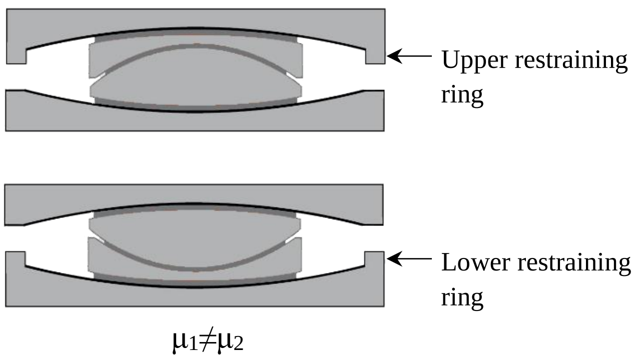

Figure 2. Double-surface friction pendulum isolators with unequal upper and lower surface friction coefficients.

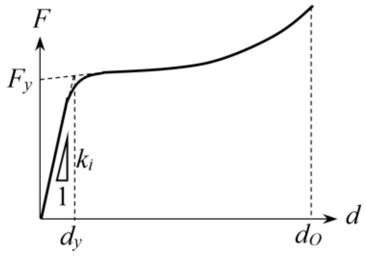

Figure 3. Force-displacement curve of metallic dampers with adaptive behavior.

In case of metallic dampers, TBDS (2019) offers a closed-form equation for calculation of cyclic dissipated energy, as follows:

$$E_S = 4n_S\eta_S F_y\left(1-\frac{K_d}{K_i}\right)\left(d_O-d_y\right) \tag{4}$$

Where F_y denotes the yield force, K_i initial elastic stiffness, K_d secondary (post-elastic) stiffness, d_O displacement, d_y yield displacement, n_s number of similar dampers, and η_s is a factor which is equal to 1.0 for metallic dampers whose hysteresis behaviour follows a kinematic hardening rule.

TBDS (2019) only addresses elastomeric and lead-rubber bearings with round sections and outlaws rectangular sections due to the possibility of high strain concentrations at corners.

6 DESIGN OF SEISMIC ISOLATION AND ENERGY DISSIPATION DEVICES, AND THEIR MINIMUM TESTING REQUIREMENTS

TBDS (2019) recognizes three methods for analysis of isolated bridges namely, Simplified analysis (SA), Modal combination analysis (MCA) and Non-linear time history analysis (NLTHA). The selection of appropriate analysis method is based on bridge category as laid out in Table 1.

Table 1. Selection of appropriate analysis method based on bridge category in TBDS (2019).

Bridge importance category (KÖS)	Bridge analysis category (KAS)		
	K (complex)	D (other)	T (Single-span straight bridges)
1	NLTHA	NLTHA	SA
2	NLTHA	MCA	SA
3	MCA	MCA	SA

NLTHA: Non-linear time history analysis
MCA: Modal combination analysis
SA: Simplified analysis

6.1 *Displacement capacity of isolation system*

Similar to EN 1998, TBDS (2019) demands consideration of increased reliability in design displacement of the isolation system, through application of reliability factors. EN 1998 suggests a value of 1.2 in case of buildings and a value of 1.5 in case of bridges. In TBDS (2019) the reliability factor is defined as a product of two reliability factors: one reflecting the uncertainties in the analysis (γ_{g1}) and the other reflecting the consequences of failure (γ_{g2}). Reliability factor γ_{g1} takes values between 1.0 to 1.1 and is related to bridge analysis category (KAS) as given in Table 2. Reliability factor γ_{g2} takes values between 1.0 to 1.1 and is related to bridge importance category (KÖS) as given in Table 3. For example, in case of an important bridge falling in complex analysis category, the overall displacement amplification factor will be:

$$\gamma_{g1}\times\gamma_{g2} = 1.1\times1.1 = 1.21$$

Table 2. Values of reliability factor γg1, based on bridge analysis category (KAS).

Bridge analysis category (KAS)		
K (Complex bridges)	D (Other bridges)	T (Single-span straight bridges)
1.10	1.05	1.00

Table 3. Values of reliability factor γg2, based on bridge importance category (KÖS).

Bridge importance category (KÖS)		
KÖS-1 (Important bridges)	KÖS-2 (Normal bridges)	KÖS-3 (Other bridges)
1.10	1.05	1.00

6.2 *Minimum testing requirements*

Prototype test program of seismic isolators in TBDS (2019), is composed of eight tests, as summarized in Table 4. In comparison to AASHTO GSID (2014), minimum testing requirements in TBDS (2019) are more stringent considering that the full earthquake test is repeated in step 5, whereas in AASHTO GSID (2014) the repetition of earthquake test involves application of three cycles at maximum displacement.

Table 4. Schedule for prototype tests of seismic isolators in TBDS (2019).

Test No.	Purpose of the test	Test load	Description
1	Maximum thermal displacement	DL+0.20×LL	20 Cycles @ Maximum thermal displacement at a speed < 5 mm/sec
2	Wind load test	Average DL (Average among all bearings)	20 Cycles @ Maximum expected tributary wind load; Test duration 40 sec, minimum
3	Braking load test	Average DL (Average among all bearings)	• 20 Cycles @ Maximum expected tributary braking load; Test duration 40 sec, minimum • Maximum expected tributary braking load hold for 1 min
4	Earthquake test	DL	3 Cycles @ 0.25d_1 3 Cycles @ 0.50d_1 3 Cycles @ 0.75d_1 3 Cycles @ 1.0d_1
5	Repetition of Earthquake test No. 4		
6	Repetition of Wind load test No. 2		
7	Repetition of Braking load test No. 3		
8	Stability test	0.9×DL DL+LL	To be performed at it displacement of d_1

6.3 *System property adjustment factors*

Property modification factors contain contributions from multiple effects. In calculation of these factors, in order to consider the remote possibility that all contributing effects assume their maximum value simultaneously, AASHTO GSID (2014) uses property adjustment factor. Partial property modification factors due to different effects which are to be multiplied to obtain the overall property modification factor are multiplied by property adjustment factor in order to reduce their value. Property adjustment factor assumes a value of 1.0 for critical bridges, 0.75 for essential bridges and a value of 0.66 for other bridges. The concept of property adjustment factor has been expanded in TBDS (2019), to allow for adoption of different values for different effects. According to TBDS (2019), upper-bound property modification factor is calculated as:

$$\lambda_{üst} = [1 + \beta_{test}(\lambda_{test,üst} - 1)] \times [1 + \beta_{ürt}(\lambda_{ürt,üst} - 1)] \times [1 + \beta_{sc}(\lambda_{s,üst} - 1)] \times [1 + \beta_{y}(\lambda_{y,üst} - 1)] \times [1 + \beta_{aş}(\lambda_{aş,üst} - 1)] \times [1 + \beta_{k}(\lambda_{k,üst} - 1)]$$

Where β factors are coefficients for consideration of likelihood of realization of extreme state for a specific effect simultaneously with extreme state of other contributing effects. β_{test} for heating and velocity effects, $\beta_{ürt}$ for consideration of manufacturing variations, β_{sc} for the temperature effect, β_{y} for the effects of aging, $\beta_{aş}$ for effect of travel and wearing, and β_{k} for the effect of contamination. β factors suggested by TBDS (2019) for rubber-based and sliding-based isolators are given in Table 2 and Table 3, respectively.

Table 2. β factors for rubber-based isolators.

Bridge importance category (KÖS)	$\beta_{aş}$ (travel and wear)	β_{k} (contamination)	β_{sc} (temperature)	β_{test} (heating and velocity)	$\beta_{ürt}$ (manufacturing variations)	β_{y} (aging)
KÖS-1	1.0	1.0	0.90	1.0	1.0	0.95
KÖS-2	1.0	1.0	0.75	1.0	1.0	0.85
KÖS-3	1.0	1.0	0.65	1.0	1.0	0.75

Table 3. β factors for sliding-based isolators.

Bridge importance category (KÖS)	$\beta_{aş}$ (travel and wear)	β_{k} (contamination)	β_{sc} (temperature)	β_{test} (heating and velocity)	$\beta_{ürt}$ (manufacturing variations)	β_{y} (aging)
KÖS-1	0.95	0.97	0.95	1.0	1.0	0.97
KÖS-2	0.87	0.92	0.87	1.0	1.0	0.92
KÖS-3	0.80	0.87	0.80	1.0	1.0	0.87

7 MINIMUM REQUIREMENTS OF SEISMIC ISOLATION AND ENERGY DISSIPATION DEVICES TO ENSURE CONTINUED FUNCTIONALITY AND SERVICEABILITY OF THE BRIDGE

In case of highway bridges, TBDS (2019), requires that under wind and breaking loads the horizontal displacement of the isolation units be limited to 1.5% of the maximum displacement capacity and not exceeding 3 mm and 5 mm in case of piers and abutments, respectively. In case of railway bridges with continues rails, the above-mentioned displacements are limited to 2 mm and 5 mm in case of piers and abutments, respectively. Should the limits be exceeded, the code suggests use of mechanical restraints (locking devices).

The code also places a limit of 3 mm on vertical displacement under live load, in case of railway bridges.

In addition to the re-centering requirements of AASHTO GSID (2014), TBDS (2019) places an additional requirement in case of bridges located at a closest distance to an active fault less than 25 km, by requiring the post-elastic period (pendulum period) to satisfy the following inequality:

$$T_d \leq 4.5 + 1.5\, d\, /\, 25 \qquad (sec.) \tag{5}$$

Where d is the shortest distance to the active fault which controls the seismic hazard.

8 SUMMARY AND CONCLUSIONS

The distinct features of the newly developed seismic isolation bridge design specifications of Turkey, TBDS (2019), in comparison to AASHTO GSID (2014) and EN15129 are laid out. The comparative study is performed for different sections of the design specifications. The comparative study revealed that TBDS (2019) differs in many ways compared to AASHTO and EN15129 including the approaches related to the seismicity and design spectra with particular emphasis on near-field effects, minimum requirements for the serviceability of bridges, property modification factors used for seismic isolation and energy dissipation devices as well as testing procedures.

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