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Applicability of equivalent linearization methods to irregular isolated bridges

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ABSTRACT

Equivalent linearization methods are widely applied to assess the seismic demands of buildings and bridges. Several regulation codes include methodologies to conduct linear analyses with equivalent structures. Normally, bridges are highly irregular structures due to the different pier heights. This study evaluates the applicability of a group of equivalent linearization methods proposed in the literature to predict the seismic response of isolated bridges with height irregularities. The isolation system is composed by lead rubber bearings. A parametric study is carried out in bridges with three types of height irregularities and combinations of relative height between piers. The bridges were subjected to a family of seismic records from a subduction zone to evaluate the equivalent elastic methods based on the results of nonlinear time-history analysis. Especial emphasis is devoted to assess the influence of the bridge irregularity on the ability of the methods to predict the nonlinear bridge demands. The results show the applicability of the equivalent linearization methods as function of the ductility demands and the height irregularity of the bridges. This study also discusses the parameter combinations that the different approaches lead to underestimate or overestimate the bridges demands.

1. Introduction

Bridges are an essential part of a country's infrastructure. The seismic response depends on several factors including the correct evaluation of the bridge demands. Despite the nonlinear time history analysis is currently considered as one of the most accurate methodologies to assess the inelastic seismic demands, it is also a highly time-consuming process. Additionally, a nonlinear time history analysis produces voluminous output data that make, in some cases, impractical the evaluation of the results. Equivalent linearization methods propose modifying the damping and stiffness of a structure and conduct linear analyses to assess the expected nonlinear demands of the structure. In last decades, the use of isolation systems has been extended all over the world, particularly for bridge structures [21,26,18]. In many countries, simply supported girders resting on elastomeric bearings compose most of the short- and medium-length existing bridges; the substitution of the bearings with isolation devices is a relatively simple process that improves the seismic safety of the bridges. Proposing an equivalent structure with an elastic behavior aims to avoid the necessity of creating refined models, which is particularly useful for practicing engineers. However, some existing or new isolated structures require nonlinear analyses to assess the bridge demands [29]. Most of the equivalent linearization methods evaluate regular building or bridge structures. This study analyzes the accuracy of fourteen linear equivalent methods, proposed in the literature, to assess the nonlinear expected demands of irregular bridges supported on lead rubber bearings.

2. Equivalent linearization methods

In general, linear equivalent methods propose a reduction of the linear stiffness and a change of the inherent damping of a structure to assess inelastic demands. Some approaches propose empirical expressions based on a secant stiffness and others adjust expressions using experimental data and analytical nonlinear analyses. This study considers seven methods that propose an equivalent period based on a secant stiffness at the maximum nonlinear displacement [7,8,16,15,17,25]; Japanese Public Works Research Institute (cited in [10]). Other methods recommend an equivalent stiffness between the elastic stiffness and the secant stiffness [9,12,11,13,14,19].

The equivalent linear expressions depend on the hysteretic behavior assumed. Most of the proposals considered bilinear behavior with null post-elastic stiffness or a positive value of post- to pre-stiffness ratio [7,11,12,13,14,16,15,25]; Japanese Public Works Research Institute (cited in [10]). Others assumed

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several hysteretic rules including strength and stiffness degradation [9,19].

Liu et al. [20] evaluated a family of linear equivalent methods in the response of isolated single-degree-of-freedom (SDOF) systems to predict the nonlinear behavior of regular buildings. The authors found that the proposals of Dicleli and Buddaram [7] and Guyader and Iwan [9] were the more accurate methods for assessing the nonlinear response of the SDOF systems.

Table 1 displays, in alphabetic order, the equations proposed by different authors. T_{eq} is the period of the equivalent system, T_0 is the elastic period of the original structure, K_{eq} is the secant stiffness at the maximum displacement, K_i is the elastic stiffness, μ is the displacement ductility, α is the ratio of the post-elastic to elastic stiffness, E_H is the hysteretic energy, E_S is the strain energy related to the secant stiffness, ξ_{eq} is the equivalent viscous damping, ξ_0 is the inherent damping (5%) and ξ_{hyst} is the hysteretic damping.

Fig. 1 displays the equivalent period and damping ratio (T_{eq}, ξ_{eq}) with $\alpha = 0.1$. The graph (a) shows, in the vertical axis, the equivalent period ratio (T_{eq}/T_0) and, in the horizontal axis, the ductility demand. T_{eq} is the equivalent period, T_0 is the elastic period of the system and ξ_{eq} is the equivalent damping ratio. In all cases, the ratio T_{eq}/T_0 increases with the increase of the ductility demand; Iwan and K-B methods present a significantly different trend for a ductility demand larger than 10. The right graph of Fig. 1(b), displays the equivalent damping in the vertical axis with the same horizontal axis. Some methods rise the equivalent damping when the ductility demand increases, and others show increases of the equivalent damping in a small range of ductility demands and reductions for higher ductility values. These differences lead to important variability in predictions of the bridge demands.

3. Bridge models and isolation system

The 3D bridge models are simply supported medium-length structures with massive abutments at the ends. The superstructure is a typical reinforced concrete (RC) slab with a compressive concrete strength of 24.5 MPa, supported on eight AASHTO type IV girders, placed at every 1.3 m, with a compressive concrete strength of 34.3 MPa. The road surface is a 0.10-thick asphalt pavement included on the slab weight. Other RC elements (diaphragms, columns and bent caps) have compressive concrete strength of 24.5 MPa. At each third and end of the span length, exist rectangular diaphragms of 0.38 m × 0.77 m. Frame elements with six degrees of freedom at each node were used to model girders, diaphragms, columns and bent caps.

The modulus of elasticity of concrete was estimated as E = 14,000 $\sqrt{f'c}$. The steel bars have yield strength of fy = 411.9 MPa. The deck has a total width of 10.6 m with a 0.18-

Table 1
Equivalent linearization methods.

Method		References	Proposed equations
Dicleli and Buddaram	D-B	[7]	$\xi_{eq} = \xi_0 + \frac{2(1-\alpha)\left(1-\frac{1}{\mu}\right)}{\pi}\sqrt{0.41\left(\frac{T_{eq}}{T_0}-1\right)}$
Gulkan and Sozen	G-S	[8]	$\xi_{eq} = \xi_0 + \frac{10\left(1-\frac{1}{\sqrt{\mu}}\right)}{50}$
Guyader and Iwan	G-I	[9]	For $\mu < 4.0$: $\frac{T_{eq}}{T_0} = 1.1262(\mu-1)^2 - 0.0224(\mu-1)^3$ $\xi_{eq} = \xi_0 + 5.0731(\mu-1)^2 - 1.0826(\mu-1)^3$ For $4.0 \leqslant \mu \leqslant 6.5$: $\frac{T_{eq}}{T_0} = 1.1713 + 0.1194(\mu-1)$ $\xi_{eq} = \xi_0 + 11.6899 + 1.579(\mu-1)$ For $\mu > 6.5$: $\frac{T_{eq}}{T_0} = 1 + 0.870(\sqrt{\frac{(\mu-1)}{1+0.10[(\mu-1)-1]}} - 1)$ $\xi_{eq} = \xi_o + 24.383\frac{0.360(\mu-1)-1}{[0.360(\mu-1)]^2}\left(\frac{T_{eq}}{T_o}\right)^2$
Hwang and Chiou	H-C	[11]	$\frac{T_{eq}}{T_o} = \sqrt{\frac{\mu}{1+\alpha(\mu-1)}}\left(1-0.737\frac{\mu-1}{\mu^2}\right)$ $\xi_{eq} = \xi_o + \frac{2(1-\alpha)\left(1-\frac{1}{\mu}\right)\mu^{0.58}}{\pi[1+\alpha(\mu-1)](6-10\alpha)}$
Hwang and Sheng	H-S	[12]	$\frac{T_{eq}}{T_0} = 1 + ln[1+0.13(\mu-1)^{1.137}]$
Iwan	Iwan	[13]	$\frac{T_{eq}}{T_0} = 1 + 0.121(\mu-1)^{0.939}$ $\xi_{eq} = \xi_0 + 5.87(\mu-1)^{0.371}$
Iwan and Gates	I-G	[14]	$\frac{T_{eq}}{T_0} = \left(\frac{1}{\sqrt{\alpha+\frac{1-\alpha}{\mu}(1+ln\mu)}}\right)$ $\xi_{eq} = \xi_0 + \left(\frac{3}{2\pi\mu^2}\right)\left\{\frac{\pi\xi_0\left[(1-\alpha)\left(\mu^2-\frac{1}{3}\right)+\frac{2}{3}\alpha\mu^3\right]+2(1-\alpha)(\mu-1)^2}{(1-\alpha)(1+\ln\mu)+\alpha}\right\}$
Japanese Public Works Research Institute	JPWRI	[10]	$\frac{T_{eq}}{T_0} = \sqrt{\frac{0.7\mu}{1+\alpha(0.7\mu-1)}}$ $\xi_{eq} = \xi_0 + \frac{2(1-\alpha)\left(1-\frac{1}{0.7\mu}\right)}{\pi[1+\alpha(0.7\mu-1)]}$
Jara and Casas	J-C	[16]	$\xi_{eq} = \xi_0 + 0.05\ln\mu$
Jara and Jara	J-J	[15]	$\xi_{eq} = \xi_0 + \eta\ln\mu \leqslant 0.30$
Kwan and Billington	K-B	[19]	$\frac{T_{eq}}{T_0} = 0.8\mu^{C_1}$ $\xi_{eq} = \frac{2C_2}{\pi}\left(\frac{T_{eq}}{T_0}\right)^2\frac{\mu-1}{\mu^2} + 0.55\left(\frac{T_{eq}}{T_0}\right)^2\xi_0$
Kowalsky	Kow	[17]	$\xi_{eq} = 0.05 + \frac{\left(1-\frac{0.95}{\mu}-0.05\sqrt{\mu}\right)}{\pi}$
Ou et al.	Ou	[20]	$\xi_{eq} = \xi_0 + \frac{2[1+\alpha(\mu-1)+\mu(1-\alpha)\ln\mu-\mu]}{\pi\mu^2[1+\alpha(\mu-1)+(1-\alpha)\ln\mu]}$
Rosenblueth and Herrera	R-H	[25]	$\frac{T_{eq}}{T_0} = \sqrt{\frac{K_i}{K_{eq}}} = \sqrt{\frac{\mu}{[1+\alpha(\mu-1)]}}$ $\xi_{hyst} = \frac{E_H}{4\pi E_S} = \frac{4Q_y x(x_d-x_y)}{2\pi K_{eq}x_d^2}$ $\xi_{eq} = \xi_0 + \xi_{hyst} = \xi_0 + \frac{2(1-\alpha)(\mu-1)}{\pi\mu[1+\alpha(\mu-1)]}$