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Structural Drift Corresponding to the Critical Excitations

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Abstract

Although the probability of the occurrence of a critical earthquake is low, the consequences of the critical excitation events are beyond the disaster. Therefore, there is a need to consider the critical excitation analysis for important structures such as power plants, infrastructure, and buildings. Indeed, one of the important criteria in the seismic design of the structures using the critical excitation is to control the maximum structural displacement. However, the required characteristics of the analysis and design of the structures are generally random variables and have many uncertainties. Therefore, the probability-based analysis should be accomplished to determine the most probable structural responses. The main objective of this research is to investigate the reliability level of steel frame buildings subjected to critical excitations. In due course, the wide range of the SDOF structures investigated subjected to real ground motions of the critical excitations. Eventually, the reliability index of structural displacement for extreme events limit state function concerning the critical excitations were computed.

Keywords: Reliability Index; Critical Excitation; Random Variables and Uncertainty; Power Spectral Density; Serviceability Displacement.

1. Introduction

One of the most fundamental goals of structural engineering design code is to provide specific provisions to preserve a rational safety level for design criteria. However, due to the existing uncertainties in loads and structural resistance properties, the probabilistic-based methods are required to perform. However, several structural design provisions are still based on deterministic considerations. In fact, the probabilistic-based methods ensure that the structure's reliability level using the structural statistical parameters (Nowak and Collins (2013).

Due to the random nature of loading, material specifications, and implementation issues, it is necessary to utilize the probabilistic-based analyses. Thus, considering the statistical parameters associated with the distribution of random variables should be determined. Considering uncertainty leads to a new way in structural analysis and design which is called reliability-based analysis. The development of reliability theory in the present age has a history of almost 90 years. In the first period, from 1920 to 1960, the gradual beginning of the theory of structural trust has been begun. Then, Cornell (1967) and Hosofer Lind (1974) provided a reliability index definition. Their suggestion is the first criterion for the size of acceptable safety factors among structural engineers. To solve the problem of the invariance of the shape of the limit state function, Hasofer and Lind (1974) transformed the problem space into a normalized space by normalizing random variables. Subsequently, Rackwitz and Fiessler (1978) conducted a study that led to the development of a gradient-based approach. In this method, which is called the HL-RF method, the problem is implicitly approached with a very good approximation. All of these methods, which require a mathematical form of a limit state function, are known as analytic methods, and this requires the mathematical closed-form of the limit state function. To solve the non-closed-form problem, the Monte Carlo assessment method has been proposed and utilized by many types of research including Nowak and Collins

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(2013), Ghasemi and Nowak (2017a, 2017b, 2018) and Soltani et al. (2020), Dori et al. (2019).

Estimating the reliability of the maximum structural displacement during an earthquake is an important issue in seismic design. In this regard, extensive researches have been carried out and their results have been introduced as simple relations in the form of increasing displacement in seismic standards (Iranian Seismic Design 2800). Galvi et al. (1995) reviewed the displacement-based design criteria for multidegree degrees of freedom structures. During the last decade, displacement-design-based approaches have been developed for a variety of structures (Sullivan et al. 2003, and Priestley1998). Studies have also been conducted on the design provisions of the structural displacement-based control using a unique limitation.

Finding an excitation earthquake that has the most critical impact on the performance of a structure which is one of the important seismic analysis concerns. An earthquake that leads to the most critical response in a structure is called critical excitation (Takewaki 2001a). The critical excitation method was first proposed by Drenick in 1970 for a single degree of freedom of linear elastic structure with viscous damping ratios in order to take into account the inherent uncertainties of the ground motions. Then, Takewaki (2001b) developed a critical excitation method for stationary and non-stationary inputs. To do so, Takewaki (2001c) considered the average squares of the system's displacement. Ashtari and Ghasemi (2013) proposed a new critical excitation approach in which the peak intensity of their power spectral density (PSD) was adjusted using Kanai-Tajimi power spectral density. Accordingly, Ghasemi and Ashtari (2014) and Ghasemi et al. (2013) proposed a new generation of the critical excitation method with continuous PSD.

Although several types of research have been conducted on the critical excitation, diminutive studies have been considered the probabilistic approaches to investigate the reliability level of the system due to the critical excitations. Therefore, in this research, it is attempted to determine the reliability level of the existing structures corresponding to scrutinize the reliability level of the structural displacement corresponding to the critical excitations. For this purpose, steel ideal buildings are taken into consideration. The properties of this structure, such as material and fabrication uncertainties are considered as random variables. In addition to the critical excitation analysis, all structure is indented to be subjected to several severe regional earthquakes such as Tabas, Manjil, Bam, and Zanjiran earthquake. Then, using the Monte Carlo simulation, the random variables are developed for reliability analysis. Accordingly, the probability of failure and the reliability index are also calculated in each case.

2. Analysis Of Linear Dynamical Systems

To determine the frequency response of the structures, the dynamic equation must be expressed in the frequency domain using the Fourier transform. In this section, an analysis of a structure of single degree of freedom with mass$M$, a damping coefficient C, and a hardness coefficient K, are recalled with consideration of a harmonic input$x = e^{i\omega t}$. The motion equation of the system can be expressed as follows:

$$M\ddot{y}(t) + C\dot{y}(t) + Ky(t) = \ddot{x}(t) \qquad (1)$$

As mentioned, the motion equation also can be written in the frequency domain using Fourier transformation.

$$-\omega^2 MH(\omega)e^{i\omega t} + i\omega CH(\omega)e^{i\omega t} + KH(\omega)e^{i\omega t} = e^{i\omega t} \qquad (2)$$

$$F(\omega) = |H(\omega)\,|^2 = \frac{1}{M[(\omega_n{}^2 - \omega^2)^2 + 4\xi^2\omega_n{}^2\omega^2]} \qquad (3)$$

where$H(\omega)$is called the frequency response function of the system. In the analysis of the random vibration of structures, the second moment expected value of the response can be derived as:

$$E[Y^2] = \int_{-\infty}^{+\infty} |H(\omega)|^2 S(\omega)d\omega \qquad (4)$$

where $S(\omega)$ is the spectral density of the considered earthquake. Accordingly, the most likely response of the system is the root mean square of the response$\left(\sqrt{E[Y^2]}\right)$.

2.1. Critical excitation of structures

In this research, the critical excitation responses are taken from the developed critical excitation method by Ghasemi (Ghasemi and Ashtari (2014), Ghasemi et al. (2013), Ashratri and Ghasmei (2013)). The proposed method is based on the linear combination of the square of the frequency response function $(F(\omega))$ and the Kanai-Tajimi spectral density function $(S_{K.T.}(\omega))$to provide a realistic continuous critical excitation. The general assumption of Ghasemi-Ashtari's method is to find the maximum input power spectral density function with regard to two main constraints: 1- Earthquake's power and 2- Earhquake's intensity

$$S_g(\omega) = \propto * F(\omega) + \beta * S_{K.T.}(\omega) \tag{5}$$

$$\bar{S} = \int_{-\infty}^{+\infty} \propto * F(\omega) d\omega + \int_{-\infty}^{+\infty} \beta * (S_{K.T.}(\omega)) d\omega \tag{5a}$$

$$\bar{s} = Max[\propto * F(\omega) + \beta * S_{K.T-L}(\omega)] \tag{5b}$$

where, $S_g(\omega)$ is the proposed continuous critical excitation using Ghasemi-Ashrati's method. The parameters α and β are computed according to the limitations of the intensity ($\bar{s}$) and power ($\bar{S}$) of the earthquake.$S_{K.T-L}(\omega)$is Kanai-Tajimi'sspectral density function using Lai's filter, which can represent the shape of the spectral density function of the stimulation of past earthquakes. Eq. 6 expresses the formulation of Kanai-Tajimi's spectral density using Lai's filter.

$$S_{K.T-L}(\omega) = S_0 \frac{{\omega_g}^4 + 4{\xi_g}^2{\omega_g}^2\omega^2}{\left(\omega^2 - {\omega_g}^2\right)^2 + 4{\xi_g}^2{\omega_g}^2\omega^2} \left(\frac{\omega^2}{\omega^2 + {\omega_c}^2}\right) \tag{6}$$

whereω_g is the dominant frequency of ground excitation, s_0 is a constant parameter and ξ_g is the damping of the ground, which represents the sharp shape of the spectral density function. And ω_c is the modified parameter of Lai's filter.

3. Implantation of Reliability Analysis for Critical Excitation

3.1. Reliability analysis

In order to predict the behavior of a structure in the seismic loading, differential equations and geometry must be constructed in conjunction with physical laws and considering. However, the structural behavior of the system does not lead to a deterministic response. In other words, the structural response is always associated with the uncertainties stemming from both load and resistance parameters. These uncertainties may come from the existing inherent uncertainties of the loads and randomness of the mechanical properties of the material, material fabrication, or involved uncertainties of the analysis method for the structural resistance.

Using a reliability analysis, a new concept of structural performance assessment has been developed. The crucial aspect of the reliability analysis is to determine the limit state function. The limit state function is the boundary between the proper and inappropriate performance of the structure. For example, on a bridge, a failure can be used as an inability to maintain traffic or population. This undesirable performance can occur in many forms of failure such as cracks, erosion, and deformation, excessive structural load-bearing, or buckling. In traditional methods, each mode of structural failure is considered. Several types of the limit states function can be taken into account as:

A) Ultimate Limit States (ULSs): It is related to the reduction of bearing capacity and is related to the failure of the structure or part of the structure. Examples of such limit states are degradation, plastic mechanism, flow, fracture, crushing of concrete; shear failure of steel shotgun, loss of overall structural stability, and buckling of the wing.

B) Serviceability Limit States (SLSs): It is associated with gradual deterioration, user comfort, and maintenance costs, and is associated with a common failure to use the structure, which itself includes excessive deformation, excessive vibration, and permanent deformation.

C) Fatigue Limit States (FLSs): It is related to the reduction of the resistance of the recurring charge. These limit states are associated with increased damage and sudden failure under repetitive loads.

D) Extreme Events Limit States (EELSs): The extreme event limit state function is related to the tremendous natural loading pheromone which will be occurred in terms of the feasible probability.

In this current study, it is intended to establish a new limit state function for reliability analysis of the existing steel structures subjected to the critical excitations. Therefore, the considered limit state function for this research can be categorized as an extreme event limit state function concerning the serviceability(displacement) control of the structures.

3.2 Structural reliability assessment

To determine the reliability index of the system it is necessary to define a proper limit state function. Because the subject of this research is the deformation of the structure; the appropriate limit state function can be established based on the structural displacement.

$$G(\Delta) = R(\Delta) - Q(\Delta) \tag{7}$$

where $G(\Delta)$ is the limit state function, $R(\Delta)$is the displacement resistance limit of the structural, and $Q(\Delta)$ represents the structural displacement due to the loading conditions.

3.3 Structural reliability assessment based on the critical excitation

Therefore, in his research, the second type of the limit state function for assessment of reliability displacement level corresponding to the critical excitation is presented as follows:

$$G_{Critical}(\Delta) = \Delta_{Critical} - \sqrt{E[Y^2]} \tag{8}$$

4. Numerical Development of The Proposed Methodology

4.1. Ground motion selection for critical excision analysis.

In this research, four severe regional earthquakes including Tabas, Manjil, Zanjiran, and Bam were considered. Table 1 tabulates the power and intensity of the considered ground motions.

Table 1
considered regional ground motions

Notation	Ground Motion	Power ($\bar{S}$)	Intensity ($\bar{s}$) $\frac{m^2}{s^3}$
A	Tabas	8.456	1.306
B	Manjil	6.488	0.461
C	Bam	6.242	0.718
D	Zanjiran	5.066	0.416

It should be noted that the damping ratio of the ground has significant results on the reliability index. Therefore, in this study, three different types of soil with a damping ratio of 0.15, 0.40, and 0.65 are investigated. Figure 1 depicts the variation of the reliability indices of the steel structures with a bracing system concerning both introduced limit state functions ($G_I(\Delta)$and $G_{II}(\Delta)$).

4.2 Case Studies

This section consists of two parts, in each part, it is attempted to consider a different type of the steel structural system with regards to the specified inputs.

4.2.1 Model of steel structure with bracing

Herein, the steel structural system with bracing is taken to account as the first type of the considered system. Fig. 1 shows one of the considered steel frames with the eccentric bracing system.

The equivalent stiffens of this system can be analytically approximated using Eq.9.

$$\mathrm{K}_t = \frac{E}{\frac{L}{A_g}+\frac{h^3}{L^2 A_c}+\frac{d^3}{L^2 A_b}} \tag{9}$$

(14) where A_g, A_c, A_b, represent the area of brace, column, and beam respectively. Also, d, h, Lshows brace's length, column's height, and beam's length. Figure 1 illustrates the reliability indices of the steel frame stiffened using the eccentric bracing system corresponding to the provisions in the Iranian Seismic Design Code (2800) and the excitation of the given critical ground motion.

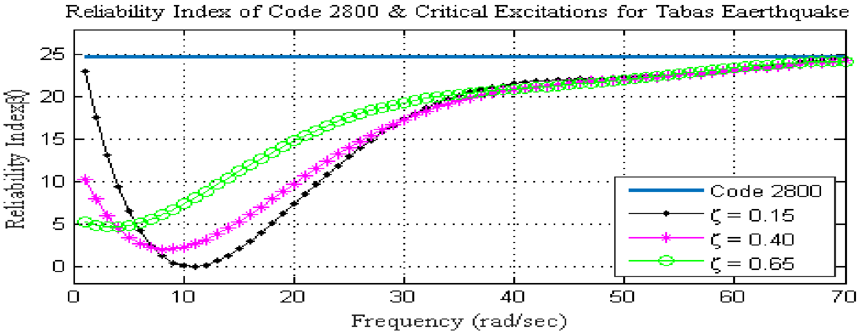

Fig.1. a.Reliability indices corresponding Tabas excitation

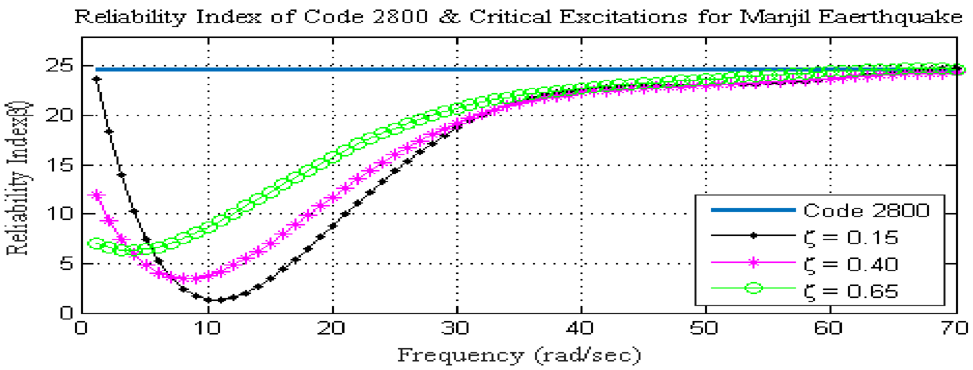

Fig.1. b. Reliability indices corresponding Manjil excitation

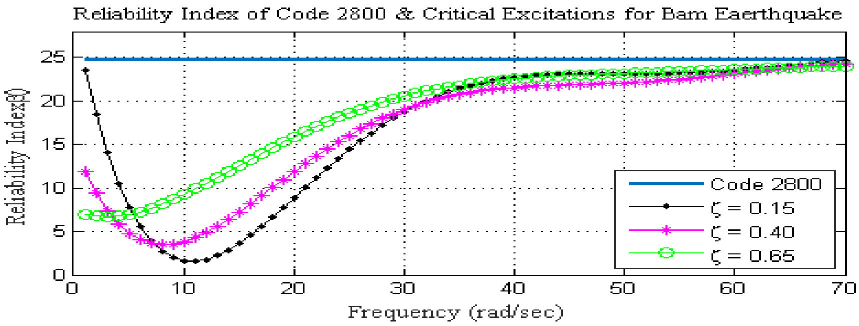

Fig.1. c.Reliability indices corresponding Bam Excitation

Fig. 1. Comparison of the reliability indices corresponding to the Code 2800 and critical excitation of the given earthquakes concerning the different damping ratio of the soils for steel frame associated with the bracing system

As can be seen, although the provided design control for the steel bracing system is far conservative, the reliability indices related to the considered critical excitations are not fallen into the consistency range. In fact, the presented reliability index of the code is not acceptable due to the extremely high range value of the reliability. Furthermore, the implemented displacement control criterion in the code does not present a consistent range of the reliability index for extreme events.

4.2.2 Model of steel shear frame

In this section, the reliability indices of the steel shear frames are investigated. The equivalent structural stiffness of shear frames can be approximated using the following equation (Eq.10).

$$\begin{cases} K_t = \frac{24EI_C}{h^3}\eta \\ \eta = \frac{12\rho+1}{12\rho+4} \quad ; \quad \rho = \frac{I_b}{4I_c} \end{cases} \tag{10}$$

where $K_t$is the equivalent structural stiffness of shear frames. And $I_c$and $I_b$are the moment inertia of the column and beam, respectively.

As it was mentioned earlier, in order to perform the reliability analysis of the structures, there is a need for statistical data of the resistance and loading parameters. Herein, the statistical parameters are collected based on the literature review [18]. Furthermore, the uncertainty of the equivalent structural stiffness is derived using the Monte Carlo simulations. Table 2 represents the required statistical parameters and equivalent structural stiffness uncertainty.

Table 2
Statistical parameters of the structure

Random Variable	E $\frac{kg}{cm^2}$	h cm	I_c cm^4	K_t $\frac{kg}{cm}$
Distribution Type	Lognormal	Normal	Normal	Lognormal
Mean	$2.04\text{x}10^6$	450	2640	714
Coefficient of Variation	0.10	0.04	0.001	0.158
Standard Deviation	$2.04\text{x}10^4$	18	2.64	113

At this stage, the index of reliability without changes in geometric conditions of the bending structure is calculated for loading critical excitation of severe earthquakes in Iran (Tabas, Manjil, Bam, and Zanjiran) and similar to the problem, a simple single degree of freedom system with bracing of the corresponding diagrams is plotted in Fig. 2.

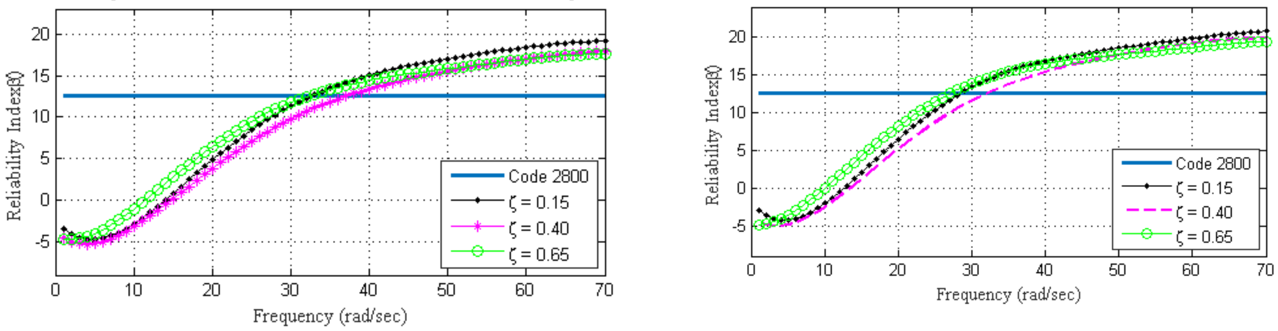

Fig. 2. a.Reliability indices corresponding Tabas excitation

Fig. 2. c.Reliability indices corresponding Bam excitation

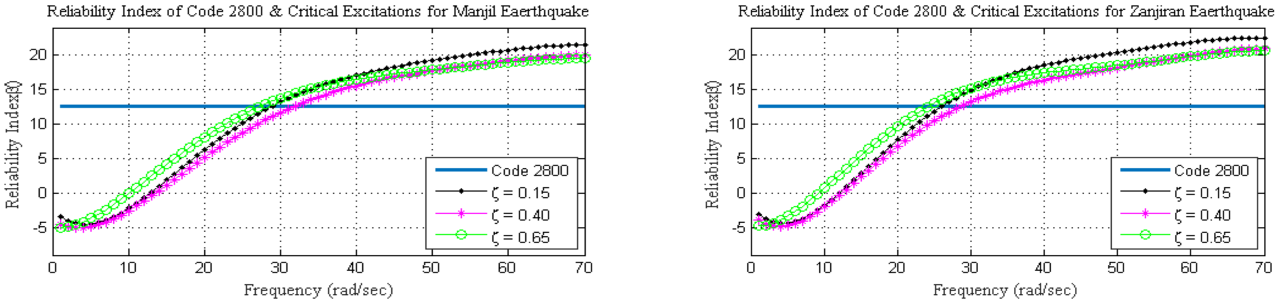

Fig. 2. b. Reliability indices corresponding Manjil excitation

Fig. 2. d. Reliability indices corresponding Znjiran excitation

Fig 2.Comparison of the reliability indices corresponding to the Code 2800 and critical excitation of the given earthquakes concerning the different damping ratio of the soils for steel share frame

According to the directed figures and data, although the given displacement control criterion in the code can lead to the acceptable reliability level, the obtained reliability indices for considered critical excitations are dramatically varied corresponding to the different main frequency range of the structures.

Table 3
The reliability index of six metal structures for loading the basis of the 2800 regulations,
the critical excitation of Tabas and the critical excitation of Manjil

Model No.	#1	#2	#3	#4	#5	#6
β_1 Reliability Index of Code 2800	3.12	2.01	2.28	0.75	1.85	2.13
β_2 Based on the Tabas's earthquake	-5.26	-5.28	-5.28	-3.44	-2.81	-1.96
β_3 Based on the Manjil's earthquake	-4.71	-4.93	-4.63	-3.27	-2.69	-1.82

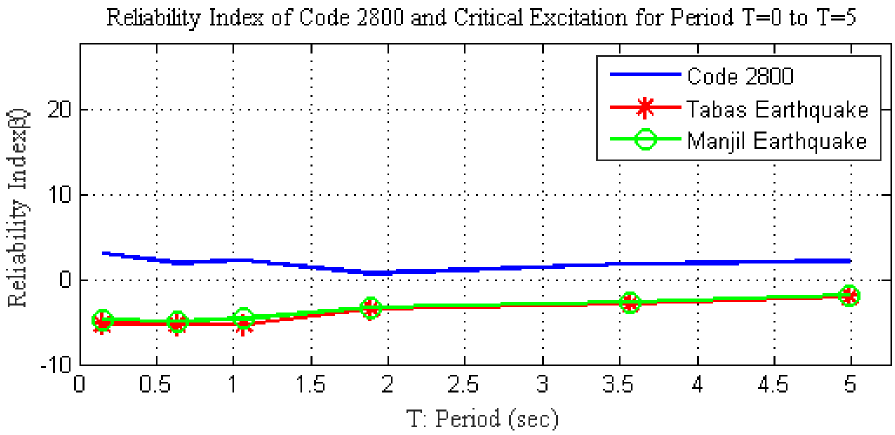

Fig.3. Indicator Reliability Index Correlation Index Correction Based on code 2800 and Critical excitation of Tabas and Manjil for the Range of Period from 0 to 5 Seconds

5. Discussion and Conclusion

The results obtained from this research can be presented as follows:

The results obtained from this research can be presented as follows:

1-In conventional methods of structural analysis, structural and loading characteristics are considered to be deterministic variables. In practice, many of the parameters have a great deal of uncertainty in their nature, that the deterministic assumption of them or the application of high confidence coefficients to cover uncertainties leads to the non-acceptable assessment. Thus, to investigate the safety of the structure, the reliability assessment is necessary to perform. Finding an excitation from an earthquake that has the most critical impact on the performance of a structure in an earthquake is one of the important issues that can be considered in the seismic analysis and design. The earthquake that leads to the most critical response in the structure is referred to as a critical excitation.

2-In this research, the reliability of SDOF steel structures in two configurations of the frame systems subjected the loading of the shear basis of the earthquake code (code 2800), as well as the critical excitation loading of large earthquakes in Iran, with potentiality and intensity considerations (Tabas, Manjil, Bam, and Zanjiran) were investigated .

3-In this research, to conduct a probabilistic analysis, the random variable of structural resistance as well as the loading scenarios were considered using the available statistical parameters.

4-In this research, the structures were designed based on the given regulations in Code 2800. Accordingly, critical loading scenarios were applied to the same structure corresponding to the wide range of ground motion frequencies. It was observed that a constant drift control criterion cannot provide a rational reliability index for a wide range of the natural structural period. Therefore, there is a need to propose a new drift-control criterion that formulates in terms of the structural natural period.

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