JOURNAL OF ENGINEERING AND APPLIED SCIENCE, VOL. 67, NO. 4, AUG. 2020, PP. 885-903
FACULTY OF ENGINEERING, CAIRO UNIVERSITY

DERIVATION OF DAMPING MODIFICATION FACTOR USING EGYPTIAN SEISMIC RECORDS

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ABSTRACT

Damping modification factor serves in international seismic codes as a transformation factor between the conventional 5%-damped elastic response spectrum and the corresponding spectra with other damping levels. This transformation process is necessary for the design of structures with high damping levels such as seismically isolated buildings. The aim of this paper is to derive expressions for the damping modification factor using the data of local earthquakes in Egypt. The ground motions used in this study included 26 natural accelerograms recorded in Egypt. In addition, 150 artificial accelerograms were generated to be compatible with the response spectra in the Egyptian code. Two separate expressions were derived for the natural and the artificial ground motions. A comparison was done between the two derived expressions and the values of damping modification factor in two international codes as well as those in previous studies. It is noted that the expression deduced using natural accelerograms gives the most conservative values beyond a time period of 2 seconds and for damping ratios higher than 10%. Consequently, the natural earthquakes expression is proposed for upgrading the Egyptian code to include design provisions for seismic isolation.

KEYWORDS: Damping modification factor, seismic isolation, Egyptian seismic code, natural and artificial earthquakes.

1. INTRODUCTION

Damping modification factor is used in seismic design of structures with base-isolation or supplemental damping devices which are used to reach a desired seismic performance with cost efficiency. Base-isolation for example can achieve low floor accelerations and low inter-storey drifts for low and medium rise buildings [1]. In such

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cases, the damping modification factor is used to adjust the 5%-damped elastic response spectra to higher damping values due to the addition of these devices. Today, there are many international seismic codes that adopt values or expressions for that factor based upon past researches. The widely adopted research [2] was applied in UBC-97 [3], NEHRP-97 [4] and IBC 2000 [5] for design of base-isolated buildings and buildings equipped with supplemental damping devices. Another research effort [6] was implemented in UBC-94 [3] and NEHRP-94 [4]. The expression deduced later [7] was adopted in Eurocode 8 (EC8) [8]. The period dependent nature of the damping modification factor was confirmed in many studies before [9, 10]. The majority of the research works on the damping modification factor topic were based on single degree of freedom (SDOF) systems subjected to natural earthquakes excitation. However, the use of artificial earthquakes as an input excitation was done [11] to compute the damping modification factor.

The objective of the current research is to derive expressions for the damping modification factor using natural earthquakes recorded in Egypt and artificial earthquakes suited to the Egyptian conditions. The importance of estimating the damping modification factor using local earthquakes' records was discussed [12]. The research done [12] included deriving expressions for the damping modification factor using the records of the Chi-Chi earthquake that hit Taiwan in 1999. In that research, the values of the damping modification factor deduced using the Chi-Chi earthquake records were compared with the corresponding values using records of earthquakes in the USA. It was concluded that Taiwan needs its own damping modification factors as the factors deduced from records in the USA are not suitable to Taiwan. By reviewing the current version of the Egyptian code for calculation of loads on Structures (ECP201-2012) [13], it was noticed that there were no seismic provisions for base isolation and supplemental damping devices. In addition, the values of the damping modification factor in the code (Table (8-4) in the code) are dependent only upon the type of building material and structural system. There is no expression to compute the damping modification factor at higher damping levels introduced by using seismic isolation or supplemental damping devices. The damping of seismic-isolated structures for example may typically range from 10% to 35% [14]. It is well known that building codes are continuously subject to developments and upgrades. The current research outcomes are devoted to help in adding provisions for seismic isolation in the upgrading process for the Egyptian code.

2. METHOD OF COMPUTING THE DAMPING MODIFICATION FACTOR

The damping modification factor (B) has other names that appeared in the previous literature such as damping adjustment factor and damping reduction factor. In this paper, it will take the name damping modification factor and will be computed using the following Eq. (1):

$$B = \frac{D(T, \xi = 5\%)}{D(T, \xi)} \tag{1}$$

Where:

D (T, ξ = 5%): maximum elastic displacement of a single degree of freedom (SDOF) system having period of vibration T and damping ratio 5% when subjected to an earthquake ground motion.

D (T, ξ): maximum elastic displacement of the same SDOF system (i.e. having the same period of vibration T) but having damping ratio ξ when subjected to the same earthquake ground motion.

The procedure of computing the damping modification factor using Eq. (1) was adopted in previous research [11] where both near-fault and far-fault records were used. For both types of records, time history analyses were done by subjecting each SDOF system to one horizontal earthquake component independently at a time. The same SDOF system is solved another time but using the orthogonal horizontal component independently. The process is repeated for all the horizontal earthquake components and no vertical components are used as the deduced damping modification factors (B) are used to get the horizontal design displacements of the isolation systems in base-isolated buildings as shown in Eq. (2). It is worth noting that according to Eq. (1), the values of the damping modification factor are usually greater than unity for damping ratios greater than 5%. However, some previous researches defined that factor using the inverse of Eq. (1) and the latter definition gives values smaller than unity for damping ratios greater than 5%.

$$S_{De}(T) = \frac{S_e(T)}{B}\left[\frac{T}{2\pi}\right]^2 \quad (2)$$

Where:

S_{De} (T): design displacement of the isolation system in a base-isolated building having vibration period T and damping ratio ξ.

S_e (T): elastic response spectral acceleration corresponding to vibration period T and damping ratio equals to 5%.

In the current study, the response history analyses for the SDOF systems were carried out using the following variables:

1- The period of vibration for the SDOF systems is varied from 0.1 to 4 seconds with a 0.02 second time increment. This period range was adopted [12] and adopting it in the current study is useful for comparison with previous studies. However, the typical period range for base-isolated buildings is 2 to 3 seconds [14].
2- Five levels for the viscous damping ratios of the SDOF systems were used: 5%, 10%, 20%, 30% and 40%.

In this paper the damping modification factor was calculated using two sets of ground motions. The first set includes natural recorded earthquakes while the second set includes artificially generated earthquakes. As seismic zone (5) in Egypt has the highest seismic risk and activity, it was then given priority for investigation in this study. Consequently, the ground motions were selected such that their epicentres lie in the regions of Gulf of Aqaba and Gulf of Suez, as the sites lying inside seismic zone (5) in Egypt are located around these two gulfs. However, the applicability of the expressions deduced in this paper to other seismic zones in Egypt should be studied in future researches using the seismological data of these zones.

3. NATURAL RECORDED EARTHQUAKES USED IN COMPUTING THE DAMPING MODIFICATION FACTOR (SET (1))

The first set of ground motions includes natural recorded earthquakes provided by the Egyptian National Seismic Network (ENSN). The data that was provided by the

ENSN included the acceleration time history records for three recent earthquakes. These earthquakes were moderate size earthquakes. The first two events struck the northern zone of Gulf of Suez near Suez city on 18 July 2014 and 22 July 2014 [15]. The third event struck the Gulf of Aqaba near Nuweibaa city on 27 June 2015 [16].

Figure 1 shows the locations of the epicentres for the three earthquakes on a satellite map. The seismological data of the three earthquakes and the stations' names are given in Table 1 including the peak ground accelerations in north-south and east-west directions. Figure 2a shows a sample from the natural accelerograms used in this study, while Fig. 2b shows the horizontal response spectra for the three earthquakes.

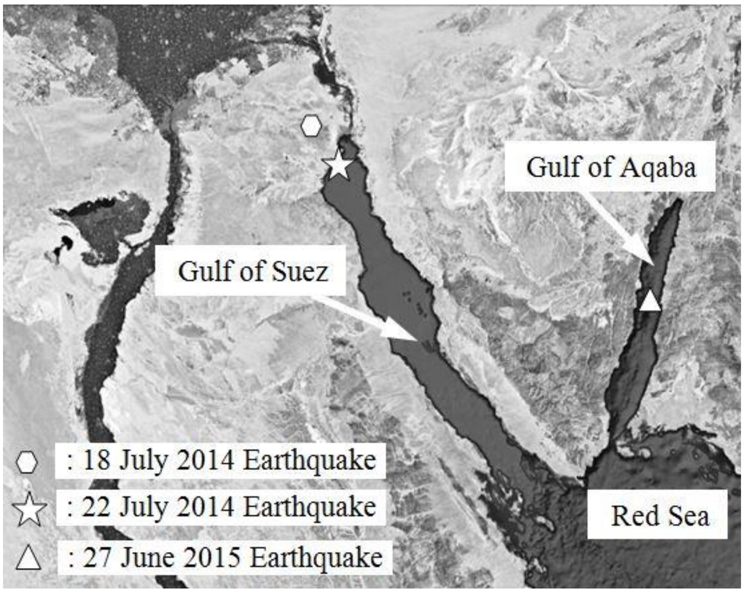
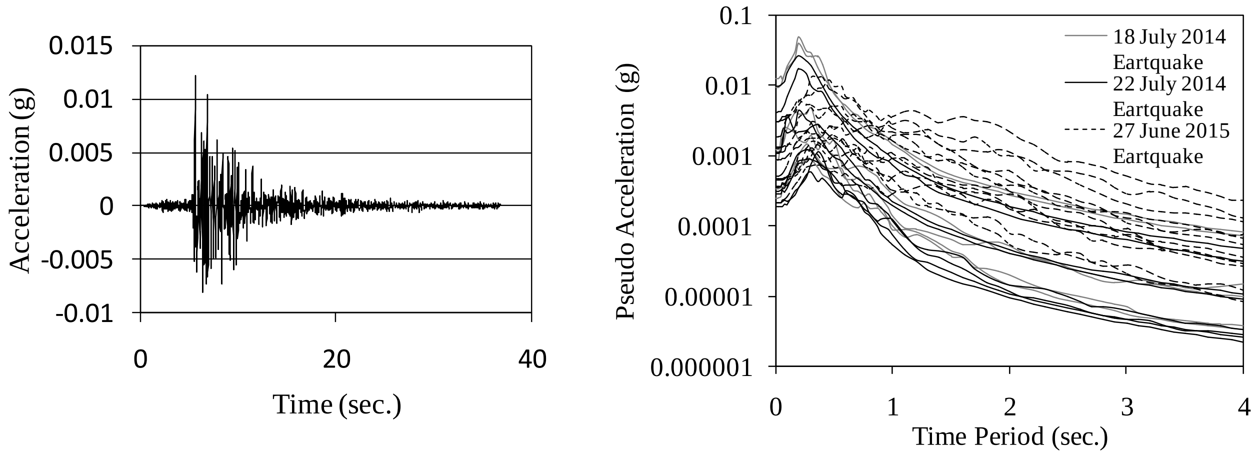


Fig. 1. Locations of the epicentres for the three recorded earthquakes.

Table 1. Data of the natural ground motions used in this study.

Earthquake date	Coordinates of source	Focal depth (km)	Moment magnitude (M_w)	Station name	Epicentral distance (km)	PGA-NS (g)	PGA-EW (g)
18 July 2014	30.03°N, 32.27°E	16	3.8	Suez	28	$1.2*10^{-2}$	$9.1*10^{-3}$
				Kawmia	87	$8.5*10^{-4}$	$1.2*10^{-3}$
				Bani Suef	153	$2.4*10^{-4}$	$3.4*10^{-4}$
22 July 2014	29.78°N, 32.42° E	20	3.7	Suez	21	$4.1*10^{-3}$	$9.8*10^{-3}$
				Katamia	55	$1.1*10^{-3}$	$1.3*10^{-3}$
				Bani Suef	148	$2.8*10^{-4}$	$3*10^{-4}$
				Sinai	158	$1.8*10^{-4}$	$2.1*10^{-4}$
27 June 2015	28.90°N, 34.74°E	14	5.2	Port Said	354	$3.1*10^{-3}$	$1.1*10^{-3}$
				Anshas	359	$3*10^{-3}$	$1.8*10^{-3}$
				Zagazig	365	$1.3*10^{-3}$	$5*10^{-4}$
				Mansoura	405	$8.7*10^{-4}$	$4.4*10^{-4}$
				Edfina	487	$4.7*10^{-4}$	$2.1*10^{-4}$
				Alexandria	531	$3.5*10^{-4}$	$3.6*10^{-4}$



(a) (b)

Fig. 2. (a) N-S component of the acceleration record at Suez station during the 18 July 2014 earthquake. (b) Response spectra for the 26 natural accelerograms.

4. ARTIFICIALLY GENERATED EARTHQUAKES USED IN COMPUTING THE DAMPING MODIFICATION FACTOR (SET (2))

The natural recorded earthquakes represent an important seismological data for calculating the damping modification factor. However, there is other form of seismological data that can be used indirectly to calculate the damping modification factor. This form includes the seismological parameters for historical earthquakes that hit Egypt before constructing the Egyptian National Seismic Network (ENSN) in 1997. The seismological parameters of historical earthquakes were used before to generate artificial ground motions [17]. In addition, artificial ground motions were used to estimate the damping modification factor [11]. As the focus of the current research is on seismic zone (5) in the Egyptian code for calculation of loads on structures (ECP201-2012) [13], then historical earthquakes that hit the northern Red sea region were selected for investigation. Two major earthquakes occurred in the northern Red sea region near the Egyptian coasts. The first earthquake is Shedwan 1969 earthquake while the second one is Aqaba 1995 earthquake. As these two events occurred before 1997, they were not recorded in Egypt. An efficient tool for creating benefit from the two above mentioned earthquakes is generating artificial accelerograms using the seismological parameters of the events.

4.1 Procedure Used for Generating Artificial Earthquakes

The process of generating artificial earthquakes requires specialized software suited for that purpose such as the SeismoArtif® version 2016 software [18] that was used in the current research. The required input in the software involves the moment magnitude (M_w) of an earthquake and the source to site distance, which are known for historical earthquakes. The resulting artificial accelerogram should be compatible with a target response spectrum. The target response spectra used in the current research are the response spectra of seismic zone (5) in the Egyptian code for calculation of loads on structures (ECP201-2012) [13]. It is worth noting that seismic zone (5) is divided into two subzones: zone (5-A) having peak ground acceleration (PGA) of 0.25g and zone (5-B) having PGA of 0.3g. Each subzone includes five target spectra corresponding to the five ground types (A, B, C, D and E) defined in the code. This choice of target spectra aims at investigating the effect of all possible ground conditions that may be present at the sites studied. In the current research, it was chosen to generate three artificial accelerograms for each single target spectrum to comply with the minimum requirements of the Egyptian code [13]. The artificial accelerograms were generated for the sites lying inside seismic zone (5) in the Egyptian code [13] as shown in Fig. 3. These are:

1- Zone (5-A) includes Sharm El-Sheikh, Hurghada and Nuweibaa cities.

2- Zone (5-B) includes Taba city and Shedwan Island.

It is seen that for each historical earthquake scenario, a total number of 75 artificial accelerograms was generated. This is because five sites were studied with five target spectra for each site and for each single target spectrum, three accelerograms were generated. As two strong historical earthquake scenarios were used, then a total number of 150 artificial accelerograms were generated in this study.

4.2 Artificially Generated Accelerograms Using the Shedwan 1969 and the Aqaba 1995 Earthquakes Scenarios

The first event used in generating artificial ground motions is the Shedwan 1969 earthquake. This earthquake occurred on 31 March 1969 with an epicentre near

Shedwan Island at the entrance of Gulf of Suez [19]. The second event used in generating artificial ground motions is the Aqaba 1995 earthquake. This earthquake occurred on 22 November 1995 with an epicentre lying inside Gulf of Aqaba near Nuweibaa city [20]. The artificial simulations for the two events were done for the five sites lying in seismic zone (5) which are shown in Fig. 3 on a satellite map with the locations of the earthquakes sources. Table 2 gives the seismological data of the two earthquakes, the distances between the epicentres and the sites studied and the peak ground acceleration (PGA) values for generated accelerograms compatible with ground type (A) spectra. Figure 4 shows a sample from the generated accelerograms for target spectrum of ground type (A).

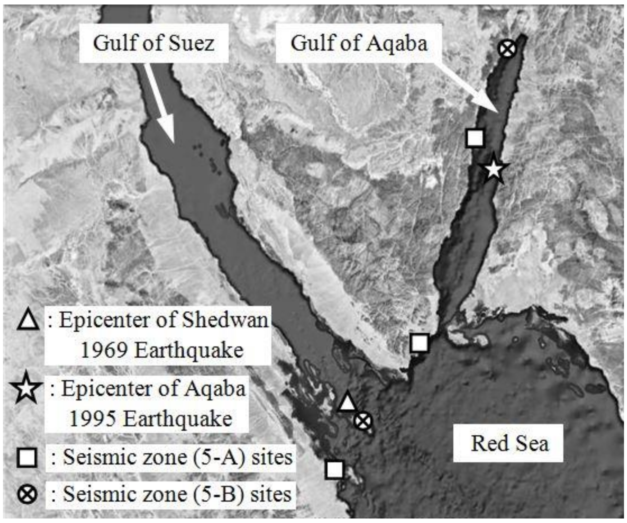


Fig. 3. Epicentres of earthquakes used in artificial simulation and locations of sites studied.

Table 2. Data of the two earthquakes used in artificial simulation.

Earthquake name	Coordinates of source	Focal depth (km)	Moment magnitude (M_w)	Site studied in seismic zone (5)	Epicentral distance for the site studied (km)	PGA (g)
Shedwan 1969	27.58º N, 33.9º E	10	6.6	Sharm El-Sheikh	56	0.27
				Hurghada	37	0.29
				Nuweibaa	172	0.23
				Taba	234	0.3
				Shedwan	15	0.36
Aqaba 1995	28.83º N, 34.8º E	18	7.3	Sharm El-Sheikh	110	0.29
				Hurghada	200	0.26
				Nuweibaa	22	0.32
				Taba	75	0.37
				Shedwan	167	0.32

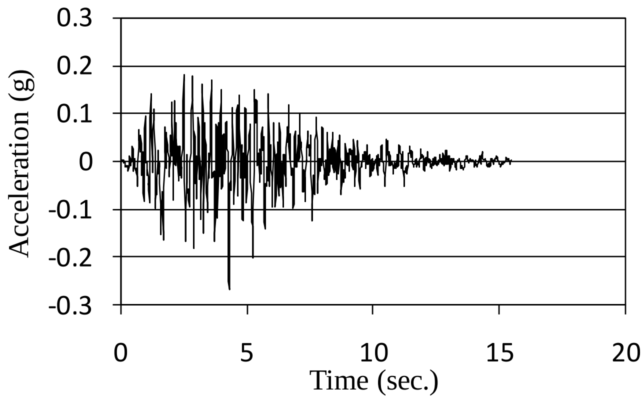


Fig. 4. Artificially generated accelerogram for Sharm El-Sheikh city using Shedwan 1969 earthquake scenario.

5. PROPOSED EXPRESSION FOR THE DAMPING MODIFICATION FACTOR USING NATURAL RECORDED EARTHQUAKES (SET (1))

The first set of ground motions (Set (1)) consists of 26 natural accelerograms (13 stations × 2 horizontal components). Each one of the 26 accelerograms was used independently to perform time history analyses for the SDOF systems with time periods and damping ratios mentioned before. The output of the time history analyses (resulting displacement time histories) were used to get the maximum displacement responses that are used in Eq. (1) to compute the (B) factor. The previous steps were repeated for every one of the 26 accelerograms separately. This gives 26 values for the (B) factor for each single combination of time period and damping ratio. The mean values of the (B) factor were computed for all the combinations [12] as shown in Fig. 5. This implies that a single point on any curve in Fig. 5 is the mean of 26 values. The dependency of the factor upon the time period and the damping ratio is clear from the figure and therefore the target expression for that factor should contain these two variables. A search for a suitable formula that fits the mean values of the (B) factor based on the reduced chi-squared values was done followed by a nonlinear regression analysis [21] and the following equation was deduced:

$$B = C_1\, T^{(C_2 + C_3\, ln\, T)} + C_4\, ln\, T \tag{3}$$

Where (T) is the time period and the coefficients C_1, C_2, C_3, C_4 are functions in the damping ratio (ξ) as follows:

$$C_1 = \sqrt{49.3 - (\xi - 7.002)^2} \tag{4}$$

$$C_2 = \frac{0.02364}{\xi} - 0.4801 \tag{5}$$

$$C_3 = -0.2432 - 0.0815\, ln\, \xi \tag{6}$$

$$C_4 = 0.4626 - \frac{0.02279}{\xi} \tag{7}$$

The plot of Eq. (3) is shown in Fig. 5 and it is clear from the figure that the equation has a good fitting with the original data.

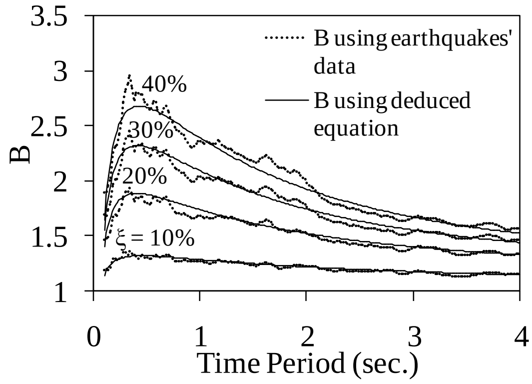


Fig. 5. Mean values of (B) for Set (1) of ground motions and values using regression.

6. PROPOSED EXPRESSION FOR THE DAMPING MODIFICATION FACTOR USING ARTIFICIALLY GENERATED EARTHQUAKES (SET (2))

The procedure done for Set (1) of ground motions was repeated for Set (2). The mean values for the (B) factor using the 150 artificial accelerograms are shown in Fig. 6. The artificial accelerograms were generated such that their spectra match the spectra of the Egyptian code (having a plateau between periods T_B and T_C). Consequently, the generation software [18] adjusts the resulting spectra to the nearest shape for the plateau and gives two peaks with fluctuating points in between. The plots for the (B) factor are affected by spectral shapes of the earthquakes from which they were calculated and this explains the two peaks in Fig. 6. These plots resemble the plots of the (B) factor using natural earthquakes in the general trend (upward convex). To model these plots using simplified normalized shape, the same expression used for Set (1) was adopted but with different coefficients (Eq. (8)).

$$B = K_1\, T^{(K_2 + K_3\, ln\, T)} + K_4\, ln\, T \tag{8}$$

Where (T) is the time period and the coefficients K_1, K_2, K_3, K_4 are functions in the damping ratio (ξ) as follows:

$$K_1 = 6.722\, ln(\xi + 1.117) \tag{9}$$

$$K_2 = 0.6561 - \frac{0.03075}{\xi} - 1.079\, e^{\left(\frac{-0.1636}{\xi}\right)} \tag{10}$$

$$K_3 = -0.05277 - 0.1854\, \xi + \frac{0.003093}{\xi} \tag{11}$$

$$K_4 = -0.413 + 0.8914\, \xi + \frac{0.000919}{\xi^2} \tag{12}$$

The plot of Eq. (8) is shown in Fig. 6 having reasonable fitting to the original data except at the peaks region.

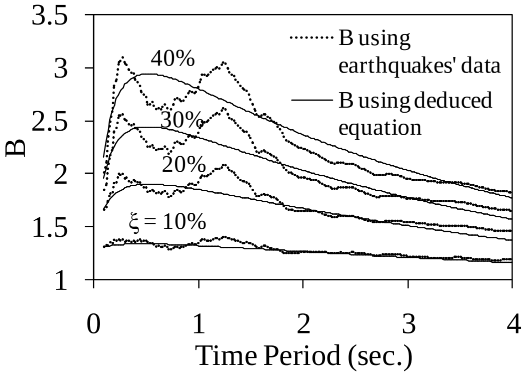


Fig. 6. Mean values of (B) for Set (2) of ground motions and values using regression.

7. DISCUSSION AND COMPARISON WITH INTERNATIONAL CODES' VALUES AND PREVIOUS STUDIES

7.1 Discussion

In order to assess the accuracy of the two derived expressions in predicting the exact values of the (B) factor obtained from response history analyses, the R^2 coefficient of determination was calculated as shown in Fig. 7a.

It is well known that a value of unity for the R^2 coefficient means exact fitting for the empirical expression with the original data. The values of that coefficient did not fall less than 0.84 which means a relatively good fitting. Also the maximum positive and negative relative errors are shown in Fig. 7b and they did not exceed an absolute value of 12% which is not high.

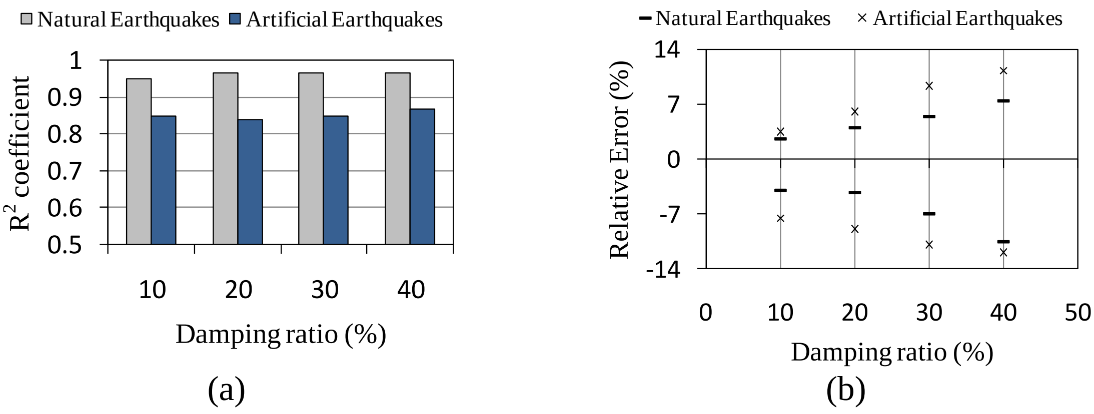


Fig. 7. (a) Values of the R^2 coefficient. (b) Values of the relative error.

7.2 Comparison with Previous Studies

Figure 8 shows a comparison between the two expressions deduced in this paper and a previous research [11]. This previous research [11] included the examination of three different ground motion databases. The first database consists of 100 far-fault accelerograms. The second database included 110 near-fault accelerograms. The third database included 100 artificial accelerograms generated to be compatible with type (1) spectrum in EC8 [8]. The expressions corresponding to the whole samples for the damping modification factor of displacement spectra [11] were used for comparison in Fig. 8. From Fig. 8, the following may be noticed:

1- The natural earthquakes equation deduced in this paper is comparable to the natural earthquakes equation in the previous research [11]. This is noted for peak values that occur nearly at the same time period and the close values for the results at time periods higher than about 1.5 seconds.

2- The artificial earthquakes equation deduced in this paper gives results, for most of the period range studied, closer to the natural earthquakes results when compared to the artificial earthquakes equation in the previous research [11].

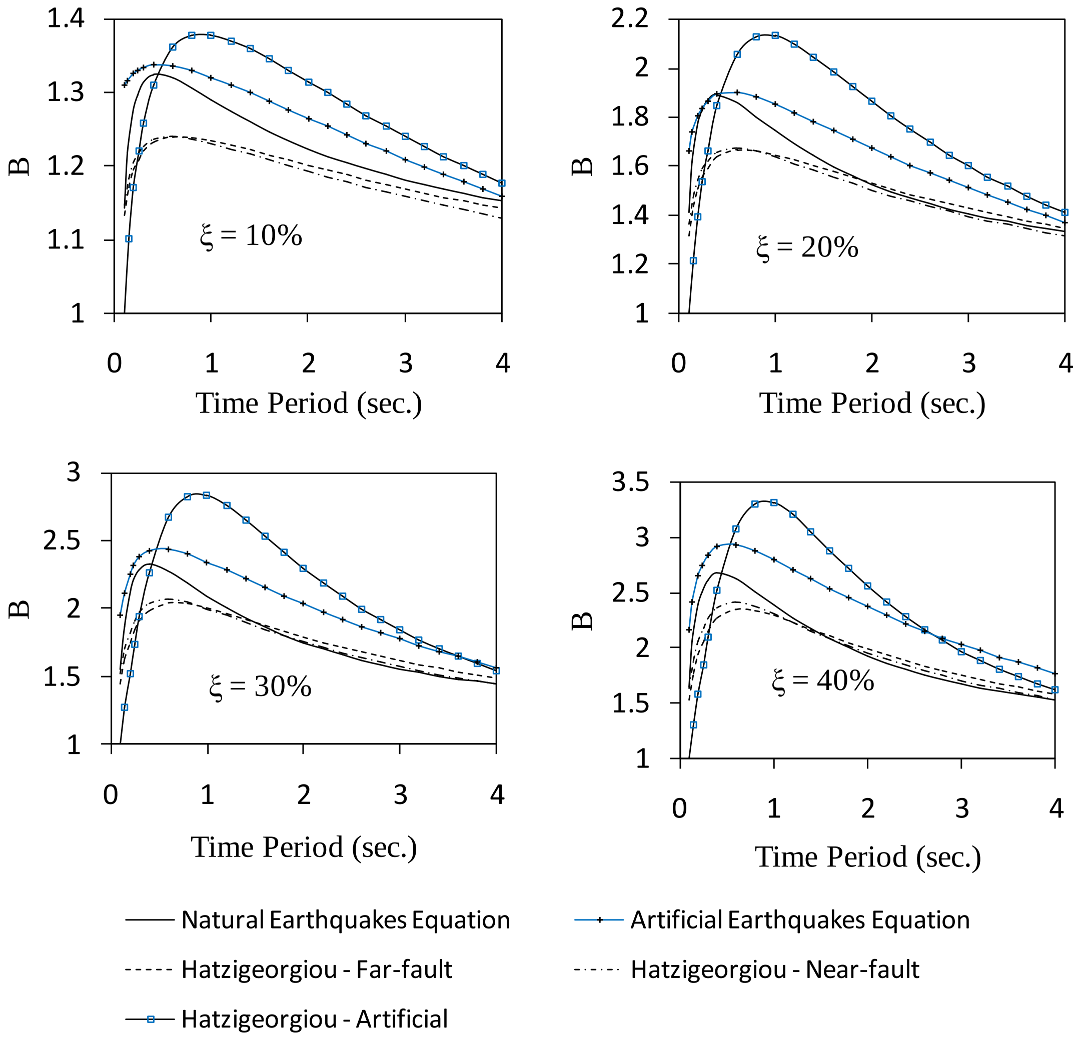


Fig. 8. Comparison between the deduced equations and [11].

The work done in this paper was also compared to another previous study [12]. Figure 9 shows a comparison between the two expressions deduced in this paper and the expressions of the previous study [12]. That research included using 338 acceleration ground motions recorded during the 21 September 1999 Chi-Chi earthquake in Taiwan to derive expressions for the damping modification factor [12]. The 338 accelerograms were classified into four groups according to the local site conditions as set in Taiwan's seismic isolation design code [22]. From Fig. 9, the following may be noticed:

1- The peak values of the plots for the natural earthquakes equation deduced in this paper and the equations derived in the previous study [12] are nearly the same but occur at different time periods.

2- It is obvious that at long time periods, both of the two equations deduced in this paper give lower values than the equations derived in the previous study [12].

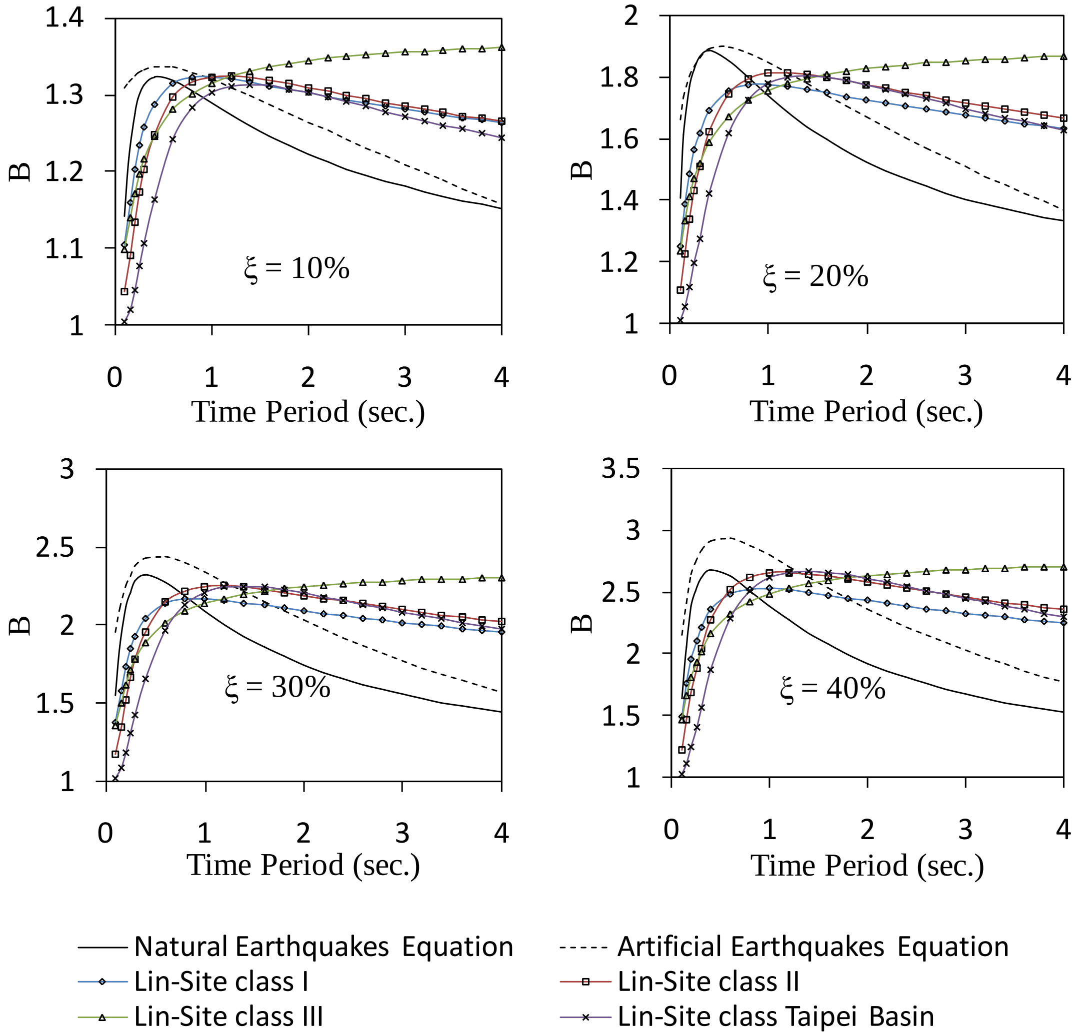


Fig. 9. Comparison between the deduced equations and [12].

7.3 Comparison between the two equations and International Codes

As two expressions for the damping modification factor were deduced using two sets of ground motions then a comparison should be made between these two expressions. In addition, some international seismic codes contain expressions or values for the damping modification factor. These values should also be compared with the values computed using the two expressions deduced in this paper. Two international codes were chosen for comparison which are IBC 2018 [5] (it refers to ASCE 7-16 [23] in the provisions of seismic isolation) and Eurocode 8 (EC8) [8]. Figure 10 shows a comparison between the two expressions deduced in this paper and the values adopted in the two international codes.

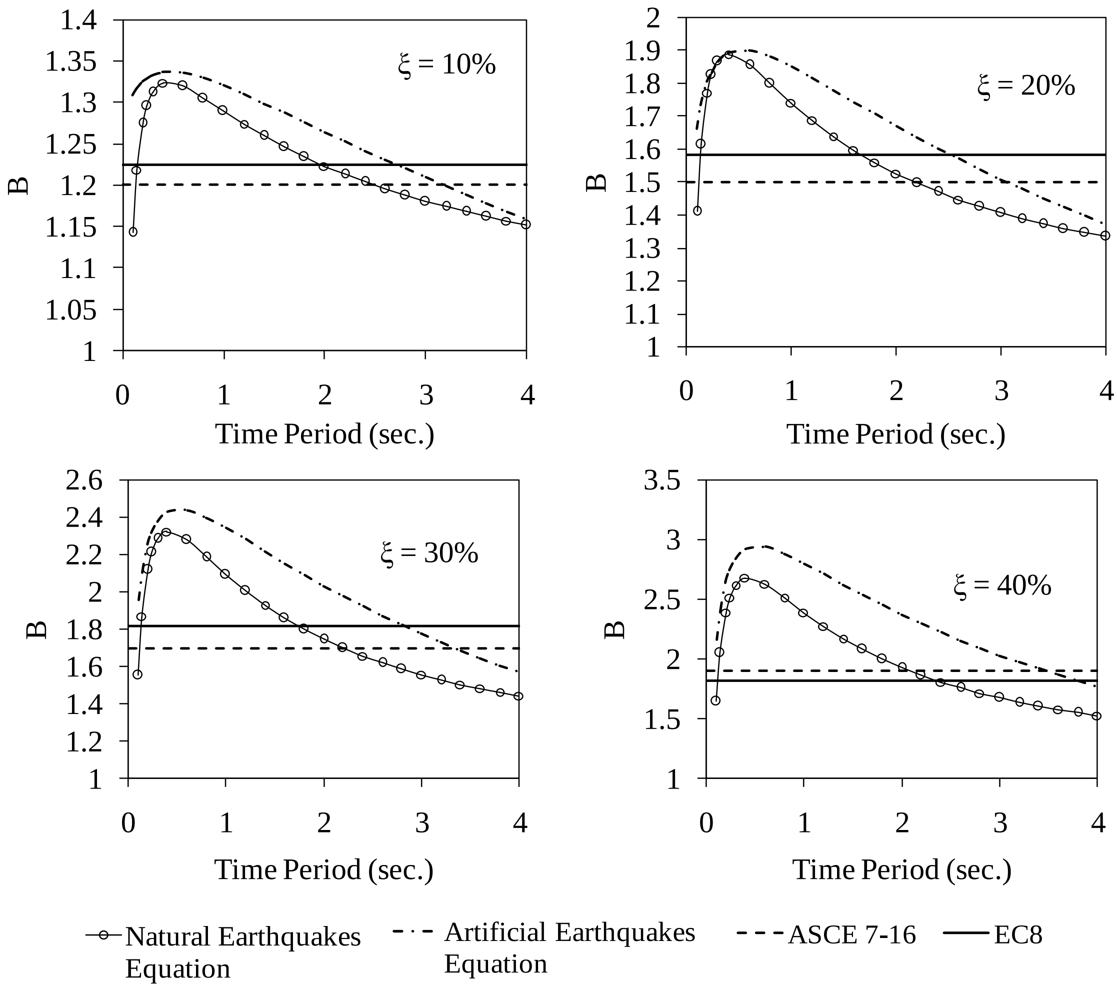


Fig. 10. Comparison between the deduced equations and two international codes.

From Fig. 10, the following may be noticed:

1- The period dependent nature for the damping modification factor is clear for the two approaches used in this paper.
2- The artificial earthquakes give higher values for the damping modification factor when compared to the natural earthquakes.

3- For time periods above 2 seconds (which is a suitable range for base-isolated buildings having more than five stories), the plots of the two equations are nearly parallel to each other and comparable to the values in the two codes. It is worth noting that the natural earthquakes equation gives the least values (most conservative as they yield the highest design displacement) in that period range. However, the maximum difference between the values of the natural earthquakes equation and the values of the two codes does not exceed 19% for that period range.

8. CONCLUSIONS

The importance of the damping modification factor in the design of base-isolated structures arises from its ability to estimate the design displacement of isolation system at high damping level from the 5%-damped displacement. In the present paper, expressions for that factor were derived by regression of the results of analyses of SDOF systems excited with two sets of ground motions. From the current study, the following conclusions may be drawn:

1- The equation deduced in this paper using natural earthquakes is more recommended to help in upgrading the Egyptian seismic provisions than the equation deduced using artificial earthquakes. It is clear from the current research and from the previous research [11] that natural earthquakes yield more conservative values for the damping modification factor than artificial earthquakes.

2- The natural earthquakes equation is applicable to zones affected by the selected ground motions due to the specific spectral shapes (frequency contents) of these ground motions. Although the current study focuses on seismic zone (5), there are also parts of other seismic zones affected by the used ground motions. The natural earthquakes equation may be applicable to the latter mentioned parts but a comprehensive study to the whole seismic zones in Egypt should be done in future researches based on more seismological data.

3- The proposed expressions for the damping modification factor have good accuracy in representing the results of the dynamic analyses for the SDOF systems. These expressions are applicable for the ranges of periods and damping ratios used in the dynamic analyses. This means that they are applicable to time periods from 0.1 to 4 seconds and to damping ratios from 5% to 40%.

4- The dependence of damping modification factor on the period of vibration is clear in the results and consistent with previous studies.

5- The two expressions deduced in this paper are in good agreement with the values of ASCE 7-16 [23] and EC8 [8] for time periods above 2 seconds.

6- The plot of the natural earthquakes equation derived in this study is comparable to the corresponding plots for previous studies [11, 12] at parts but not all of the period range studied. This means that results deduced from earthquakes recorded in Egypt are not identical with those of universal earthquakes. Therefore, it is not recommended to use universal earthquakes in deriving damping modification factors for Egypt.

7- The two equations derived in this paper are comparable to each other especially for time periods above 2 seconds where the two plots are almost parallel with maximum difference in the values of 20%. This means that in case of lack of natural records, artificial earthquakes may be used to derive values for the damping modification factor. However, these values should be adjusted to be as conservative as those resulting from available natural records for regions having similar seismicity to the zone studied.

ACKNOWLEDGMENTS

Great thanks are to the Egyptian National Seismic Network at the National Research Institute of Astronomy and Geophysics for providing the acceleration data used in this study. The Seismosoft Ltd. and the GraphPad Software, Inc. are greatly acknowledged for providing access to the software used in this study.

DECLARATION OF CONFLICT OF INTERESTS

The authors have declared no conflict of interests.

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استنتاج معامل تعديل الاضمحلال باستخدام سجلات زلزالية مصرية

يهدف البحث لاستنتاج معادلات معامل تعديل الاضمحلال في كودات الزلازل العالمية لتحويل طيف التجاوب المرن المعرف في الكودات عند نسبة اضمحلال ٥٪ إلى الطيف المناظر عند نسب اضمحلال أخرى مبنية على بيانات الزلازل في مصر حيث تم استخدام ٢٦ سجل زلزالي للعجلة مسجلين في مصر وتخليق ١٥٠ سجل زلزالى اصطناعي للعجلة بحيث تتوافق مع طيف التجاوب بالكود المصري وتم استنتاج معادلة منفصلة لمعامل تعديل الاضمحلال لكل من السجلات الزلزلية الطبيعية والاصطناعية ونتائج المعامل مقارنة من المعادلتين مع المعامل فى اثنين من الكودات العالمية وفى دراسات سابقة وظهر أن المعادلة المبنية على الزلازل الطبيعية أكثر تحفظاً عند زمن دوري أعلى من ثانيتين ونسب اضمحلال أعلى من ١٠٪ يقترح استخدامها فى تحديث الكود المصري.