16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N°4907
Registration Code: S-A1462984296

Equivalent Viscous Damping for Self-Centering Precast Concrete Segmental Bridge Columns

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Abstract: A new type of precast segmental concrete bridge column has been proposed for accelerated bridge construction in regions of high seismicity. The proposed column adopts unbonded post-tensioning to decrease prestress loss when subjected to large lateral displacements. An option is provided to either use partially unbonded conventional mild steel or high performance steel energy dissipation bars to increase hysteretic energy dissipation. The amount of added energy dissipation is controlled so that the column maintains self-centering capability. A new hysteretic model is developed in this research for the proposed column. With the developed model, the equivalent viscous damping of the proposed column is investigated and compared to that of conventional monolithic columns.
Keywords: *Bridge columns; segmental construction; equivalent viscous damping.*

1. Introduction

Precast concrete system as a well-known solution to accelerate a bridge construction in the heavy traffic area offers many advantages. It can provide a good quality of concrete structures with durability and efficient result, and also an eco-friendly structure by shifting most of the cast-in-place concrete structure to the concrete factory [1]. Basically, precast segmental column system consists of many short sections of precast concrete and compiles into one column. Precast segmental bridge column in high seismicity region is particularly discussed in this paper.

Precast segmental concrete bridge column system has been used over past years as one of economical solution to reduce large residual displacement after major earthquake. Several researchers have been worked on how to improve the serviceability of this type of column when applied in high seismic regions. Hewes and Priestley [2], Kwan and Billington [3], Ou et al. [4], Chou and Chen [5], Elgawady and Sha'lan [6] use unbounded post-tensioning system to prevent significant loss of column strength while undergo a large residual displacement and it will also maintain the column to be self-centered. Although this system produces much smaller energy dissipation compare to the conventional column with adequate ductile capacity designed for seismic resistance, it is still one of exceptional solution to keep the bridge structure back to its shape after the major earthquake happened. To increase the energy dissipation, Ou et al. [7] and Chou and Chen [5] use continuous mild energy dissipation bar across the segment joints without implanted to the foundation. Test result by Ou et al. [4] showed that ED bar contribution to the column increased as the hysteretic ED capacity and residual drift increased. However, ED bar contribution ratio should not exceed 35% to maintain the self-centering capability. In other hand, Mariott et al. [8] used replaceable external mild energy dissipation bar along the surface base of the segmental column. It is observed that the external energy dissipation bar can increase the energy dissipation of

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the system and also can offer a handy solution to be applied on the segmental column. However, external energy dissipation bar may affect the aesthetic of the bridge structure since it is built on outside of the column.

In evaluation or design of a reinforced concrete structure, displacement-based approaches offer a better accuracy compared with force-based approaches. In dsipalcement-based appraoches, it is necessary to estimate maximum displacement of a structure. There are two approaches available to estimate maximum displacement with nonlinear static procedures. The first method is displacement coefficient method which is popularly used by Velestos and Newmark [9], Miranda [10], Chopra and Goel [11], and Whittaker et al. [12]. Displacement coefficient method allows the maximum deformation in inelastic system to be similar to that of a linear system times a modification factor which associated with lateral strength and natural period of the structure [13]. The other method is equivalent linear system used in ATC-40 procedure. This method was first introduced by Jacobsen [14] and later was improved by Rosenblueth and Herrera [15], Gulkan and Sozen [16], Iwan [17], Kowalsky [18], Guyader and Iwan [19], and other researchers. In this paper, the later method will be used to capture the maximum displacement of the nonlinear behavior of proposed column.

There are two important parameters in equivalent linear system; equivalent period and equivalent viscous damping. Equivalent viscous damping by Jacobsen can be achieved from equating the energy dissipated of hysteretic steady-state cyclic response to a given displacement level to the equivalent viscous damping of the substitute structure [20]. Since Jacobsen's approach is based on physical behavior of nonlinear SDOF system, this approach becomes more appealing as basic form of equivalent linear system. In 1964, the first concept of secant stiffness at maximum response was introduced by Rosenblueth and Herrera to obtain equivalent period [15]. In secant stiffness method, the equivalent period is derived based on secant stiffness at maximum displacement of SDOF system. The concept of secant stiffness method to determine equivalent period is also used by Dwairi et al. [21]. Dwairi et al. modified Jacobsen's approach with inelastic time history analyses to estimate the equivalent viscous damping for certain structures.

The purpose of this paper is to introduce a new hysteretic rule which represents the nonlinear behavior of precast segmental bridge column. Along with the new hysteretic rule, equivalent viscous damping as one of the parameter of equivalent linear system for proposed column is investigated by certain periods, ductility, post-yielding stiffness coefficient, and ED bar ratio. To see the serviceability of the proposed column, the results will be compared to that of conventional monolithic column.

2. Structural models and ground motion selections

2.1 Structural Model

In this study, a self-centering precast segmental bridge column for seismic region is proposed. The proposed column consists of precast concrete segments, unbounded post-tensioned tendons to maintain self-centering behavior, and energy dissipation bar (ED bar) to increase energy dissipation of this column.

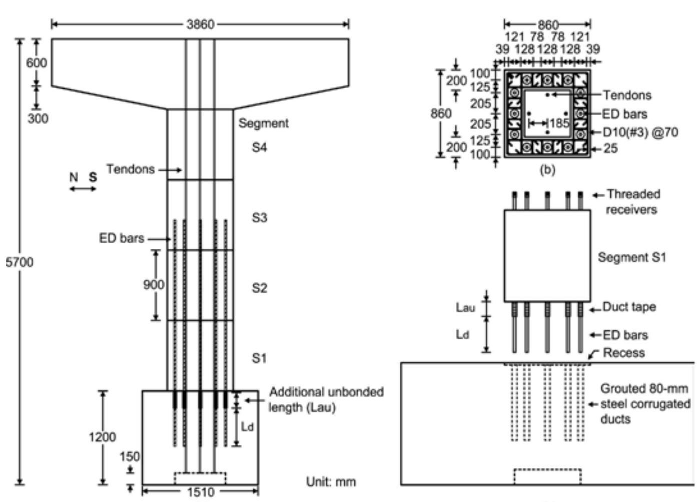


Figure 1. Major design details [22]

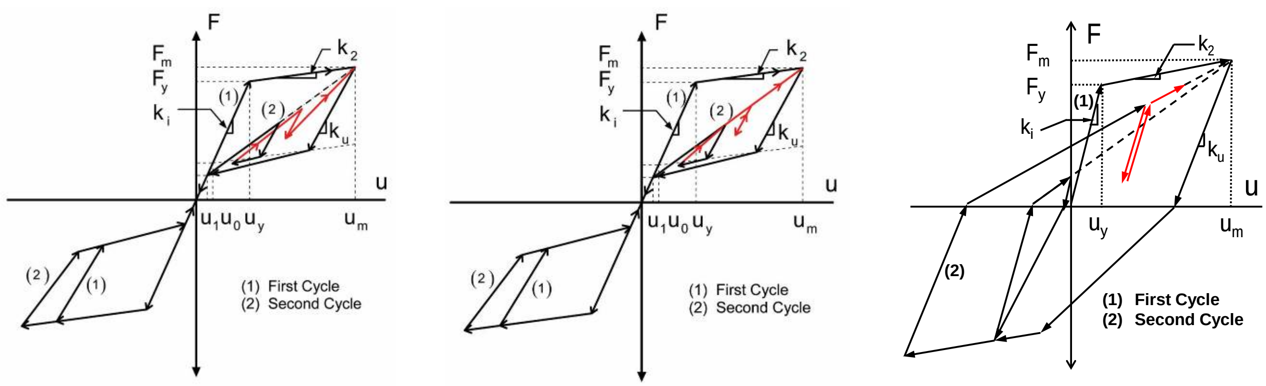
The ED bar is made of conventional mild steel or high performance steel which place continuously across segments of the proposed column. The amount of the mild steel will be controlled such that the proposed column can achieve self-centering capability. The proposed self-centering precast segmental column is shown in Figure 1. In order to investigate the nonlinear behavior of proposed column, conventional monolithic concrete column is used as benchmark and the properties of conventional column will be maintained to have the same compressive strength with that of proposed column.

2.2 Ground motion selection

There are 72 ground motions used in this study consisted of famous ground motions from United States, Japan, and Taiwan. The ground motions are selected to cover many characteristics such as near-fault high intensity peak ground motion acceleration (PGA), far-fault high intensity PGA, low intensity PGA, duration, and epicenter distance [23].

3. Hysteretic models

It has been observed by Ou et al. [24] that the precast segmental column with unbounded post-tensioned tendon and energy dissipation bar when subjected to cyclic loading showed a stiffness-degrading flag-shape hysteretic behavior. This type of hysteretic behavior is introduced as stiffness-degrading self-centering (SDSC) rule by Ou et al. in 2007 [24] which is shown in Figure 2(a). SDSC model only involves the degradation of stiffness in unloading and reloading part after the first cycle which has the full shape of flag-shape type and in the second cycle to the end will change to approximately partial shape of the shape in first cycle. The first version of SDSC hysteretic rule considering the direct reloading will go to all-time peak displacement. However, this rule leads the hysteretic behavior to produce negative energy dissipation which can underestimate the equivalent viscous damping. In 1975, Mahin and Bertero [25] proposed that the reloading path should be directed to the peak of last cycle instead of the peak of all former cycles. This rule can be applied as long as the former path has larger reloading stiffness. Hence, the reloading path directed to former peak instead of peak-all cycles rule is applied to the original SDSC model as seen in Figure 2(b).



(a) (b) (c)

Figure 2. Hysteretic models; (a) SDSC model by Ou et al. [25], (b) Modification of SDSC model (MSDSC), and (c) Modified Clough-Takeda (MCT) model

In Figure 2, F_y = yield strength of structure; F_m = peak strength; k_i = initial stiffness, k_2 = post-yielding stiffness; k_u = stiffness corresponding to peak displacement; and u_0, u_1, u_y, u_m (are displacement components. The relationships of the SDSC hysteretic model parameters can be seen as follows

$$\beta = \frac{u_y - u_0}{2u_y} \tag{1}$$

$$u_1 = u_0 - 0.35u_y\left(1-\beta\right) \tag{2}$$

$$u_m = \mu u_y \tag{3}$$

$$k_2 = \alpha k_i \tag{4}$$

$$k_u = k_i \left(\frac{u_y}{u_m} \right)^{\gamma} \tag{5}$$

For $\beta =$ energy dissipation bar ratio; $\alpha =$ post-yielding coefficient; $\gamma =$ stiffness degradation coefficient; and $\mu =$ ductility. In other hand, to represent nonlinear behavior of conventional column, Modified Clough-Takeda (MCT) hysteretic model is used which is shown in Figure 2(c). Modified Clough-Takeda model is based on Modified Clough hysteretic model which considers the peak-oriented rule combined with the rule of Takeda hysteretic model which consider the degrading unloading stiffness in the system. This hysteretic model is modified to match with the MSDSC hysteretic model which considers peak-oriented rule and degrading unloading stiffness.

4. Parametric study to identify equivalent viscous damping

To represent maximum displacement of MSDSC hysteretic behavior, the equivalent linear system is used. Based on secant stiffness method, there are two important parameters in equivalent linear systems which are equivalent period or effective period (T_{eq}) and equivalent viscous damping ratio (ξ_{eq}). Equivalent period of the system can be obtained from Eq. (6).

$$T_{eq} = T_{eff} = T_i \sqrt{\frac{\mu}{1-\alpha-\alpha\mu}} \tag{6}$$

where $\mu =$ ductility, $\alpha =$ post-yielding stiffness coefficient, and $T_i =$ initial period. In other hand, equivalent viscous damping ratio (ξ_{eq}) is contributed by both elastic damping ratio (ξ_{el}) and hysteretic damping ratio (ξ_{hys}). The damping ratio which is not captured by the hysteretic model in nonlinear analysis is called elastic damping ratio (ξ_{el}). The amount of elastic damping ratio used in the system is usually around 0.02 to 0.05 which depends on the type of the structure [26]. In other hand, ξ_{hys} represents the damping ratio captured by hyteretic behavior after the system yields. The basic formula of equivalent viscous damping is shown as follows,

$$\xi_{eq} = \xi_{el} + \xi_{hys} \tag{7}$$

The elastic damping ratio used in this paper is 5% which based on tangent stiffness proportional damping. It is been investigated by Priestley and Grant [27] that elastic damping ratio based on initial stiffness proportional damping will lead to overestimation of equivalent viscous damping and underestimate maximum displacement. Hence, tangent stiffness proportional damping gives more correct alternative.

4.1 Parameters of SDOF system

As shown in Table 1, parameters such as ED bar ratio, post-yielding stiffness coefficient, and unloading stiffness coefficient are calibrated based on cyclic loading results obtained by Bu et al. in 2016 [28].

Table 1. Parameters to obtain the equivalent viscous damping of MSDSC model

T_i (sec)	μ	β (%)	α	γ	Ground motion
0.2-2	2	4	0	0.6	72 [23]
	4	25	0.05		
	6	35	-0.01		

The ductility input data are ranged from the least ductile structure to high ductile structure. Energy dissipation bar ratio 4% represents self-centering system with small energy dissipation close to zero and 35% ED bar ratio represents the maximum energy dissipation of MSDSC model can obtained while maintains self-centering behavior and small residual drift [22]. However, in this study only 25% ED bar ratio will be carried to show the nonlinear behavior of precast segmental column compared to that of conventional column.

4.2 Procedures to obtain equivalent viscous damping

Two analyses are involved in this procedure which are nonlinear analysis and linear analysis. Both nonlinear analysis and linear analysis will be simulated by MATLAB program. The procedure can be seen in Figure 3. In the nonlinear analysis, the initial parameters are set with elastic damping 5% and run the program until satisfiying the target ductility equal to ductility output. The analyses are carried out for 72 ground motions which are normalized with multiplier *s*. The output of nonlinear system will be the input for linear system. The equivalent viscous damping final is obtained from iteration of initial equivalent viscous damping when the target ductility is equal to output ductility.

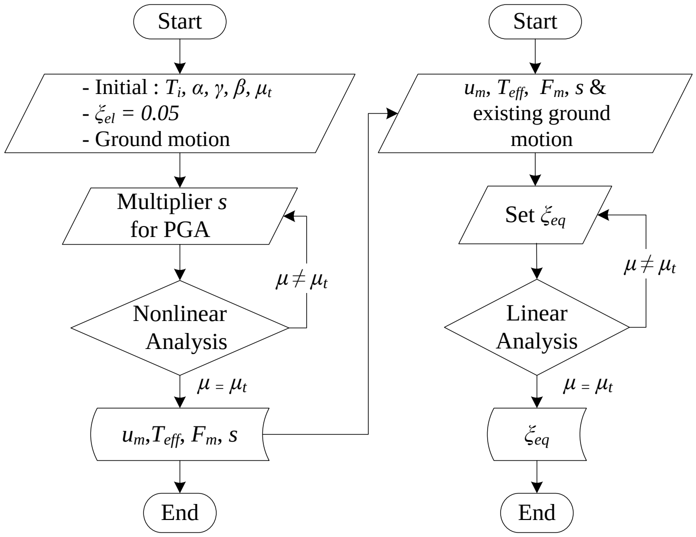


Figure 3. Procedure to obtain equivalent viscous damping

Based on Figure 3, relationship among the outputs of nonlinear analysis are described as follows,

$$k_{eff} = m\left(\frac{2\pi}{T_{eff}}\right)^2 \tag{8}$$

$$F_m = k_{eff} u_m \tag{9}$$

Where $m =$ mass, k_{eff} = effective stiffness at maximum response, T_{eff} = effective period, and F_m = maximum strength. Based on Eq. (8) and Eq. (9), secant stiffness method is used to determine effective period. Effective period based on secant stiffness method means effective period at maximum response of the system.

4.3 Analysis results

As shown in Figure 4, the analysis results of MCT and MSDSC are presented with one standard deviation. Each damping corresponds to the period is based on average value of equivalent viscous damping of 72 ground motions. The elastic damping used in the analyses is 5% with energy dissipation bar ratio 25%. The analysis results are presented based on various parameters discussed in section 4.1. There are some points to be noted based on the analysis results as follows:

- It is expected that MCT hysteretic model will produce higher equivalent viscous damping than that of MSDSC hysteretic model since MCT hysteretic model has bigger damping area. However, the gap of equivalent viscous damping values between MCT and MSDSC was quite small at μ = 2.
- The analysis results showed a wider range of the results based on its standard deviation. This scatter result was also found in nonlinear behavior of Ring Spring hysteretic model by Blandon [29]. Blandon stated that the small damping area of this type could be the reason. The small changing of a parameter in this type could significantly change the result. Moreover, the various earthquake records based on different characteristics also affected the scatter results of equivalent viscous damping.
- For both MCT hysteretic model and MSDSC hysteretic model, the analysis results showed that the equivalent viscous damping increased significantly with the increase of ductility. This means the damping will increase to suppress the increase of maximum displacement of the system.
- For various post-yielding stiffness coefficients, the $\alpha = 0.05$ exhibited the smallest equivalent viscous damping and $\alpha =$ -0.01 gave the highest equivalent viscous damping compared with the other coefficients. Generally, equivalent viscous damping decreased as the post-yielding stiffness coefficient increased and vice versa. This happened because the stiffer the post-yielding stiffness coefficient was, the smaller the damping area would be.

- It is also observed that short period less than 0.6 second produced higher equivalent viscous damping than that of period larger than 0.6 second. Moreover, equivalent viscous damping values of period larger than 0.6 second tended to close to constant values. This behavior proved that equivalent viscous damping was period dependent in short period and period independent in long period.

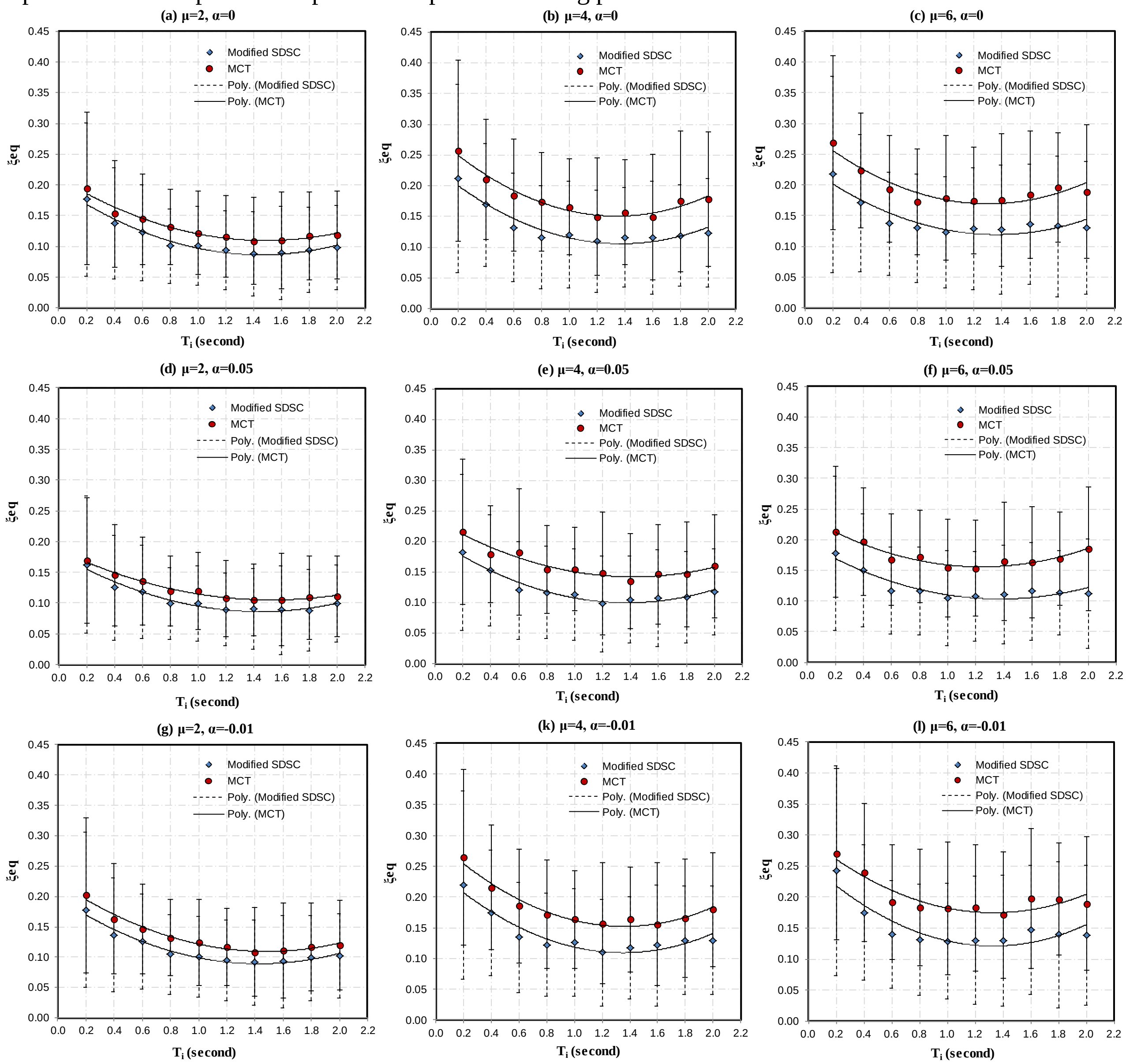


Figure 4. Analysis results of equivalent viscous damping for both MSDSC and MCT hysteretic models

4.4 Equivalent viscous damping based on area based viscous damping (ABVD)

Area-based viscous damping (ABVD) or known as Jacobsen's equivalent viscous damping approach is believed by many researchers as one of the simpliest and most applicable method to determine equivalent viscous damping since it close to the physical behavior. ABVD is an approach to approximate the steady-state response of a damped nonlinear system. The equivalent viscous damping corresponding to the hysteretic behavior can be achieved by equating the energy dissipated by an inelastic system to that by an equivalent viscous system [14, 20] as shown in Eq. (10). Hence, the equivalent viscous damping based on ABVD can be obtained by Eq. (11) with elastic damping is 5%.

$$\xi_{hys} = \frac{1}{4\pi}\frac{E_D}{E_s} \tag{10}$$

$$\xi_{eq} = 5\% + \frac{1}{4\pi}\frac{E_D}{E_s} \tag{11}$$

The ratio of actual data for both MSDSC and MCT hysteretic models are presented in Figure 5. The relationship among the results are based on various parameters which are determined in section 4.1.

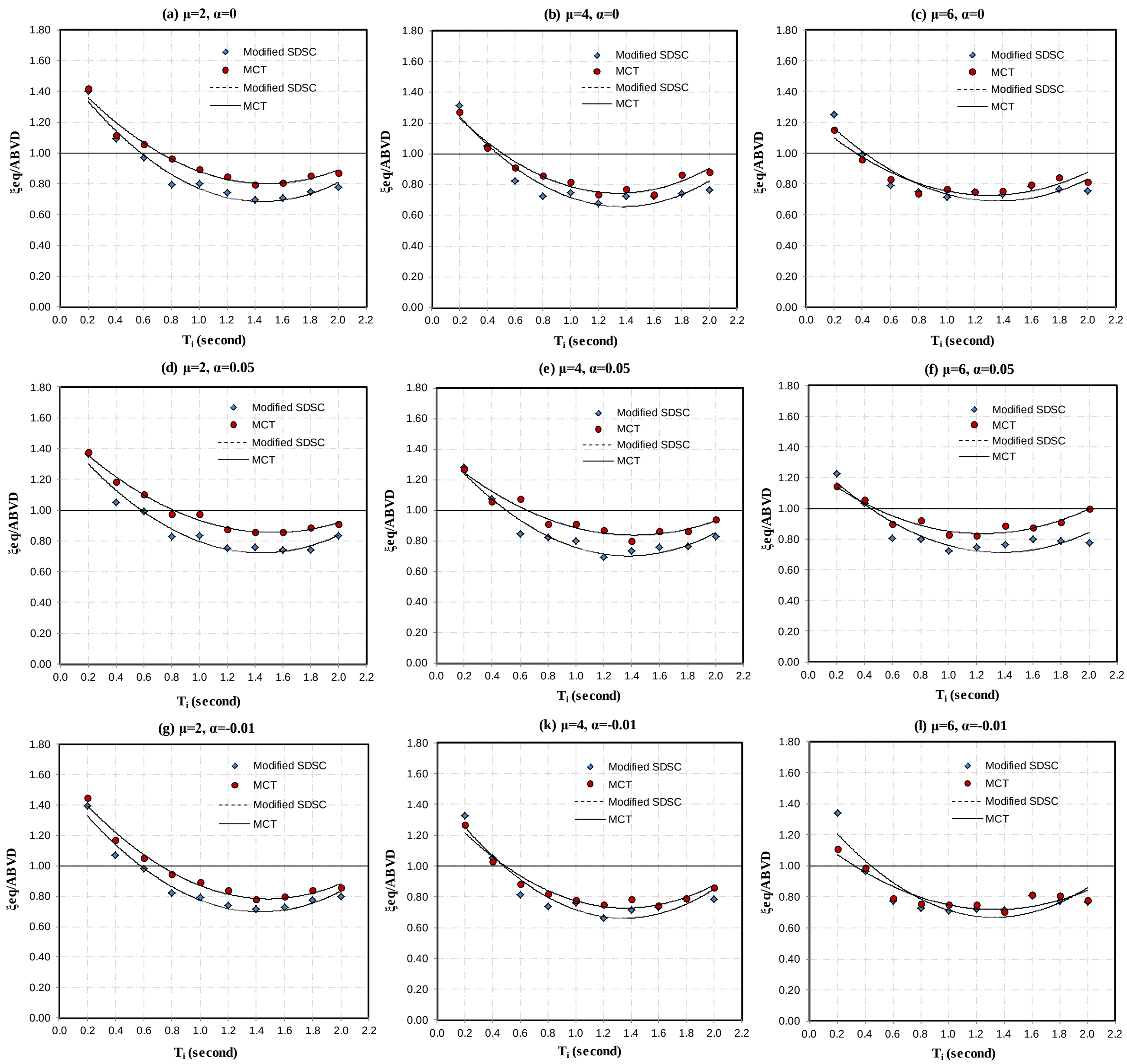


Figure 5. Ratio of equivalent viscous damping of actual data to ABVD

As shown in Figure 5, For both MSDSC and MCT, area-based viscous damping (ABVD) approach underestimated the equivalent viscous damping at around $T_i \leq 0.6$ second. However, the opposite behavior was noticed for $T_i > 0.6$ second which exhibited underestimation of the damping. The underestimation of damping at short period led the overestimation of maximum displacement and vice versa. The same cases have also been found in the study done by Dwairi et al. [21] and Blandon et al. [29]. Dwairi et al. stated that the Jacobsen's approach or ABVD underestimates the displacement in long period not only due to the overestimated damping, but also due to the shift in the hysteretic loops as the oscillator starts vibrating around a new equilibrium position.

Coorresponding to the post-yielding stiffness coefficient, the decrease of post-yielding stiffness coefficient exhibited a wider gap between ABVD and actual data in longer period. It means the increase of post-yielding stiffness will give smaller loop of damping area and smaller loop tends to produce a closer result to the ABVD. It is also explained the reason why the ratio of actual data to ABVD between MSDSC model and MCT model have a close gap between each other.

5. Summary and conclusion

An analyitical study on the equivalent viscous damping of self-centering precast concrete segmental bridge column is presented in this paper. Two hysteretic models were carried which are modified stiffness-degrading self-centering (MSDSC) and modified Clough-Takeda (MCT). Analysis results show that MCT hysteretic model produced higher equivalent viscous damping than that of MSDSC hysteretic model. Other important conclusion are listed below,

1. Both MCT model and MSDSC model are ductility and period dependent.
2. The analysis results show a scatter behavior. This may occur because a small changing in the small damping area will increase the damping significantly and also because the earthquake records are based on various characteristics of ground motion.
3. The increase of post-yielding stiffness coefficient will reduce the equivalent viscous damping. This is due to the area of the damping becomes narrow as the post-yielding stiffness becomes stiffer.
4. The equivalent viscous damping results based on area-based viscous damping of Jacobsen approach exhibite an underestimation damping at short period and overestimation damping at long period.

6. Acknowledgement

This work was financially supported by the Ministry of Science and Technology of Taiwan, the National Natural Science Foundation of China under Project Grant No. 51208268, Transportation Science and Technology Project of Ningbo City under Grant No. 201507, Natural Science Foundation of Ningbo City under Grant No. 2015A610293.

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