SEISMIC RESPONSE MITIGATION OF BRIDGES WITH TUNED MASS DAMPERS

A. Matin (1), S. Elias (2), R. Rupakhety (3) S. Ólafsson (4)

(1) PhD Candidate, Earthquake Engineering Research Centre at University of Iceland, amj@hi.is
(2) Post PhD Scholar, Earthquake Engineering Research Centre at University of Iceland, said@hi.is
(3) Professor, Earthquake Engineering Research Centre at University of Iceland, rajesh@hi.is
(4) Professor, Earthquake Engineering Research Centre at University of Iceland, simon@hi.is
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Abstract

The article aims to investigate seismic response mitigation of bridges with tuned mass damper (TMD) schemes. A three-span reinforced concrete (RC) bridge is modelled and subjected to a number of earthquake ground excitations with different characteristics. Three TMD schemes namely single TMD (STMD), distributed multiple TMDs having equal masses (ed-MTMDs), and distributed multiple TMDs having equal stiffness (sd-MTMDs) are installed for response mitigation purpose. The coupled system is solved by numerical (Newmark's Beta) integration method. The effect of peak ground acceleration (PGA) of earthquake excitations on performances of the TMD scheme is studied. In addition, the effect of frequency content of ground motion on effectiveness of the TMD schemes is studied. Displacement and acceleration at mid-span and shear force at the base of piers are the response of interest for performance assessment. It is found that MTMDs schemes are significantly effective in reducing the base shear as compared to the STMD scheme.

Keywords: Bridge, Earthquake, Reinforced Concrete (RC), Tuned Mass Dampers, Vibration.

1. Introduction

Base isolation is a commonly used technique for mitigating seismic response of bridges. Several researchers have investigated seismic performance of base-isolated (BI) bridges. Wang et al. [1] stated that BI bridges in their study performed well under several earthquake ground motions. Seismic response of of BI bridges with elastomeric and sliding systems [2-6] has been investigated by many researchers. These studies confirmed that base-isolation system is effective to reduce inertia force demands on the superstructure of RC bridges. Base isolation system makes the overall system flexible thereby reducing structural acceleration and the corresponding inertia forces. As a cost of reduced stiffness, displacement demand increases, and excessive bearing displacement can become a concern. Controlling displacement of such bridges using different methods is investigated in recent times. [7-11]. These studies show that tuned mass dampers (TMD) can effectively reduce displacement demand of base isolated structures without having adverse effect on their acceleration demand. However, in case of other devices that issue was reported that upon reducing the large displacement, the acceleration of the system magnified.

A detailed literature review of passive TMDs is given in Elias and Matsagar [12]. Seismic response control of structures by TMDs is also well-established and numerous techniques have been presented (see, for example, References [13 and 14]). Single TMD might not be robust against uncertainties in structural properties. Multiple TMDs which are tuned to a wide band of frequencies are more robust [15].

Application of TMDs for dynamic response mitigation of bridges has been reported in many studies [16-21]. Matin et al. [22] present a study of distributed TMDs (d-MTMDs) for seismic response mitigation of bridges. They reported that d-MTMDs are better than single or multiple TMDs placed at mid-span. The study was based on a few selected ground motions. Performance of such devices against ground motion with different amplitude and frequency content is not well understood. This paper attempts to investigate this issue. To study the effect of uncertainty in ground motion, a set of 100 recorded earthquake ground motions described in Saha et al. [23] is used.

2. Mathematical Modelling

In this study, a reinforced concrete (RC) continuous span bridge is considered. The assumptions made in the mathematical modeling of the RC bridge are as follows.

1. The RC bridge without/with the TMD(s) are assumed to remain in elastic range.
2. The bridge without/with the TMD(s) are modeled by dividing the deck and piers into several small discrete elements interconnected at nodes. Two mutually orthogonal degrees of freedom in the horizontal directions are considered at each node and the mass of each adjacent element is lumped at the node [22].

Figure 1 presents a schematic diagram of the adopted model. In the figure, $k_{d\text{-}x}$, $k_{d\text{-}y}$, $c_{d\text{-}x}$, and $c_{d\text{-}y}$ are the stiffness and damping of a TMD respectively in x-longitudinal and y-transverse directions. The mass of the ith TMD is m_i.

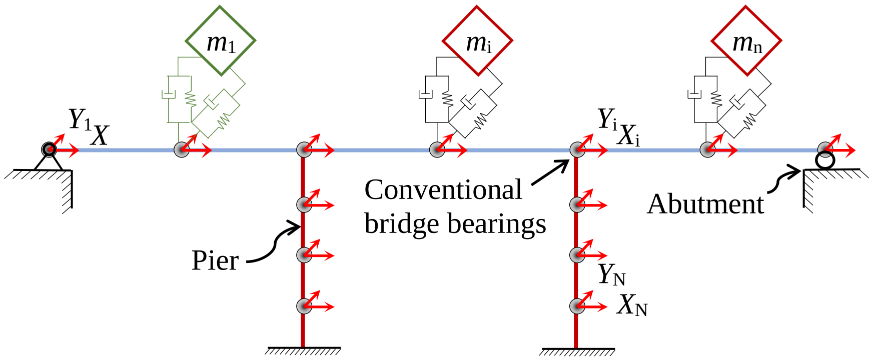

Fig. 1 –RC bridge installed with TMDs

The equations of motion for the coupled system, subjected to ground motion is,

$$[M_s]\{\ddot{Q}\} + [C_s]\{\dot{Q}\} + [K_s]\{Q\} = -[M_s]\{r\}\{\ddot{Q}_g\} \tag{1}$$

where mass, damping, and stiffness matrices of the bridge, are $[M_s]$, $[C_s]$, and $[K_s]$, respectively. The matrices are of order $(2N+2n)\times(2N+2n)$; N and n designate the degrees of freedom (DOF) of the RC bridge and the TMDs, respectively. The displacement, velocity, and acceleration vectors, are $\{Q\}$, $\{\dot{Q}\}$, and $\{\ddot{Q}\}$, respectively; and $\{\ddot{Q}_g\}$ is the ground acceleration vector in the longitudinal direction, $\{r\}$ is the influence coefficient vector. Equation 1 is solved in time domain using Newmark's integration method The location of the TMDs is as in Matin et al. [22]. The optimal parameters of the TMDs are taken from the formulation provided by Sadek et al. [24]:

$$f_{opt,i} = \frac{1}{1+\mu_i\varphi_{iu}}\left(1-\zeta_i\sqrt{\frac{\mu_i\varphi_{iu}}{1+\mu_i\varphi_{iu}}}\right) \qquad i = 1 \text{ to } n \tag{2}$$

$$\zeta_{d,opt,i} = \varphi_{iu}\left(\frac{\zeta_i}{1+\mu_i} + \sqrt{\frac{\mu_i}{1+\mu_i}}\right) \qquad i = 1 \text{ to } n \tag{3}$$

where ζ_i, φ_{iu}; $f_{opt,i}$, $\zeta_{d,opt,}$, $\mu_i = m_i / M_t$, and M_t are the damping ratio, and normalized amplitude of mode shape in the i^{th} mode of the bridge; optimum tuning frequency ratio, optimum damping ratio, the mass ratio of the i^{th} TMD, and total mass of the bridge, respectively.

3. Results

Preliminary results and their interpretations are presented in the following.

3.1 Effect of PGA on Performance of TMDs

The selected ground motions have peak ground acceleration (PGA) in the range 0.025g to 1.08g, with g representing acceleration due to gravity. The effect of PGA on performance of TMD schemes in reducing the base shear is presented in Figure 2. It is seen that that is a poor correlation between PGA and the effectiveness of the different TMD devices in reducing base shear. While the schemes work well in some cases, they don’t provide any benefit in other cases. When the PGA is less than about 0.5g, the average reduction in base shear is around 10%. For higher PGAs, the reduction in base shear is not significant. The three cases, single TMD (STMD) placed at the middle of each span, distributed multiple TMDs having equal masses (ed-MTMDs), and distributed multiple TMDs having equal masses (sd-MTMDs), are compared. Some devices perform better than others in certain ground motions, but overall all the schemes seem similar on the average and not effective. Similar conclusions can be made about mid-span acceleration and displacement demand as shown in Figures 3 and 4.

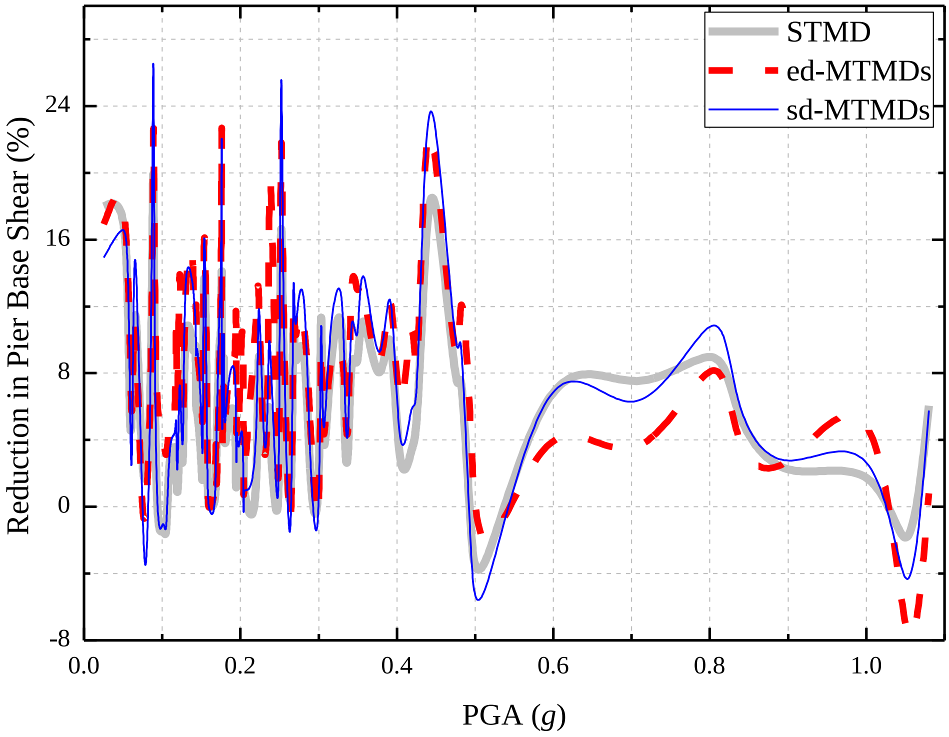

Fig. 2 – Effect of PGA on performance of the TMDs in reducing the pier base shear

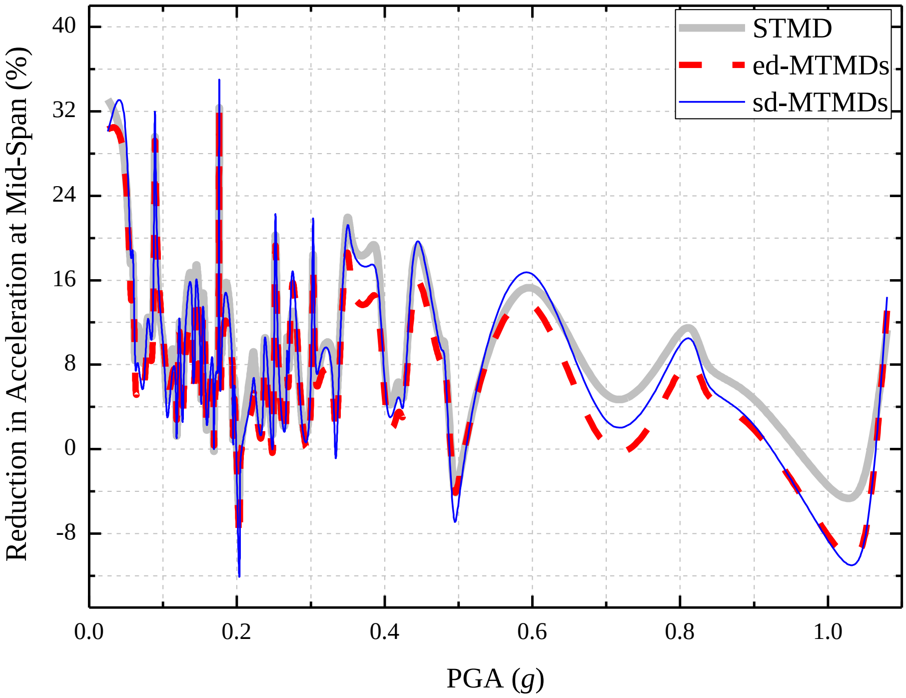

Fig. 3 – Effect of PGA on performance of the TMDs in reducing the acceleration at mid-span

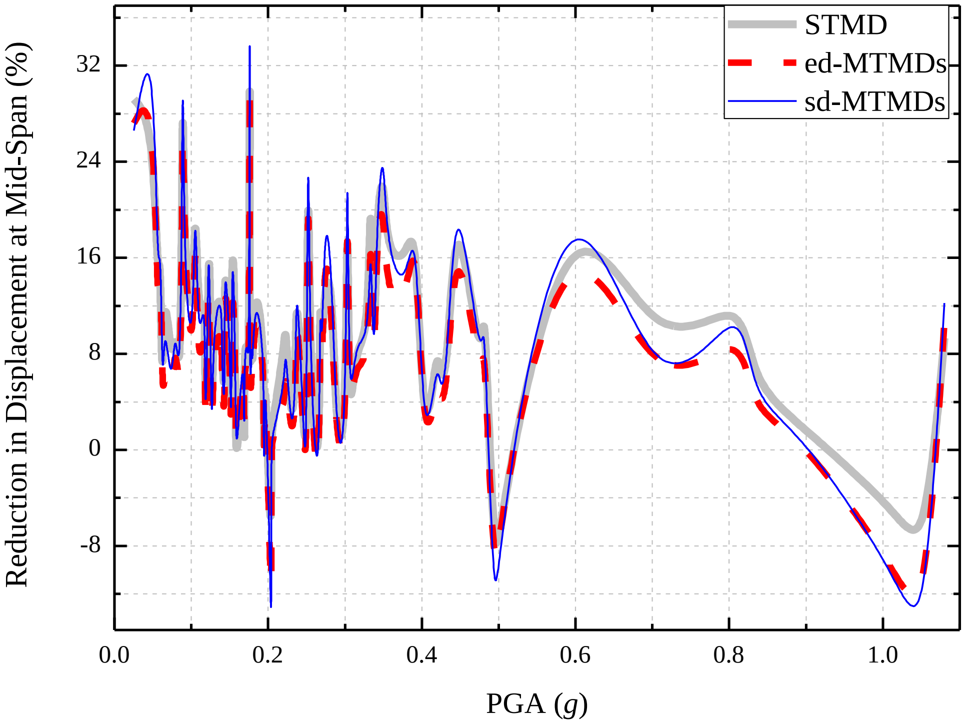

Fig. 4 – Effect of PGA on performance of the TMDs in reducing the displacement at mid-span

3.2 Performances of TMDs

To further illustrate the effectiveness of the different TMD schemes, probability distribution functions of percentage reduction in different response parameters are presented in Figures 5-7. The average reduction in base shear is around 4 to 5%, which is rather insignificant. In about 10 out of 100 cases, the reduction in base shear is about 25%. Similar conclusions can be made about other response parameters. This makes it clear that the TMD schemes used in this work are not effective in controlling response of the bridge to different types of ground motions.

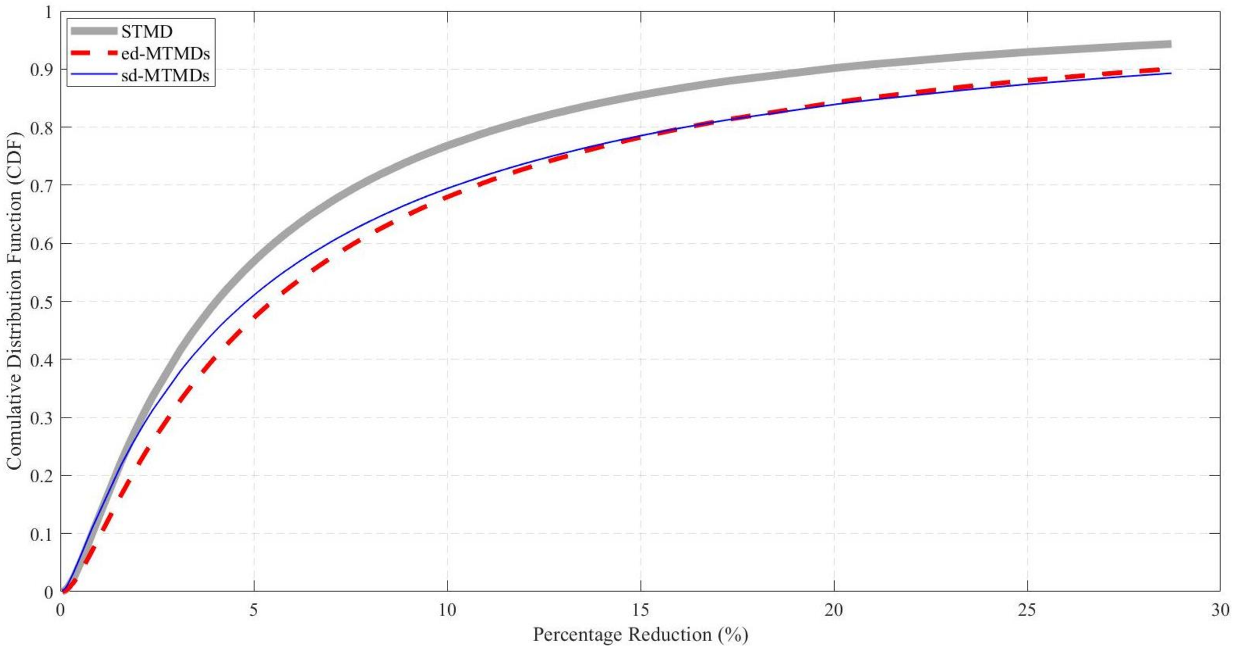

Fig. 5 – Probability distribution function of percentage reduction in pier base shear

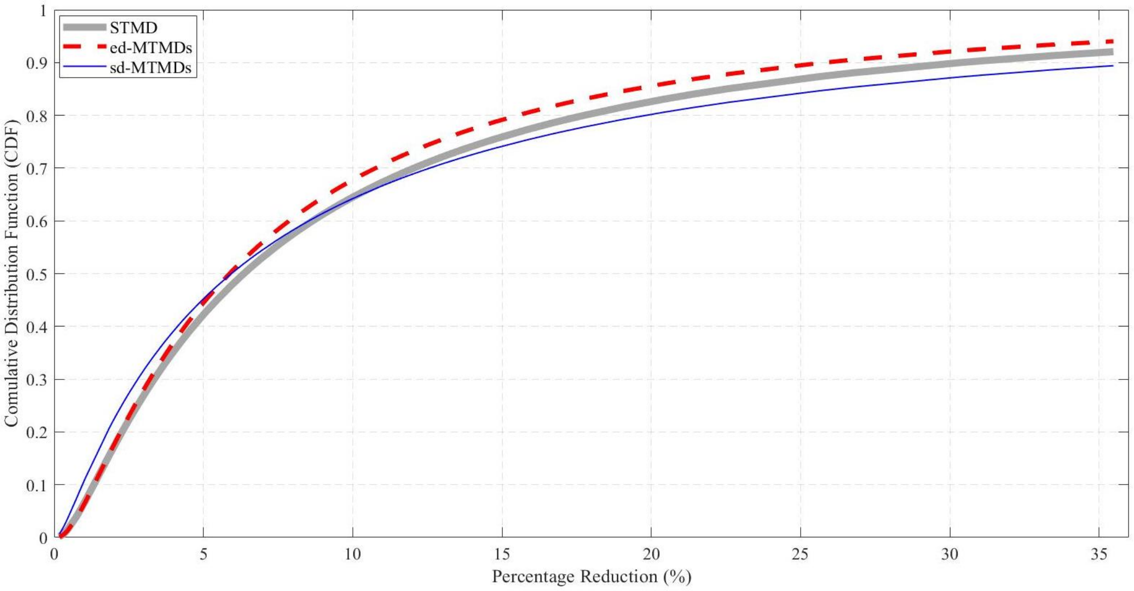

Fig. 6 – Probability distribution function of percentage reduction in mid-span acceleration.

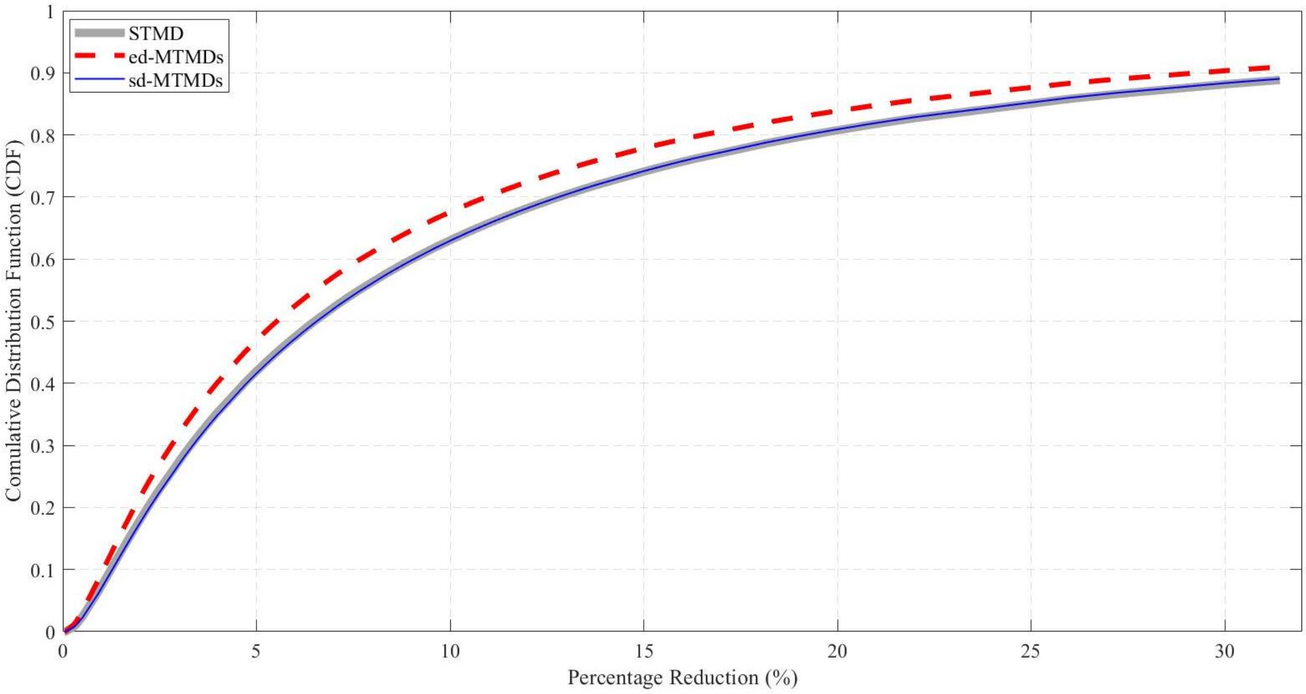

Fig. 7 – Probability distribution function of percentage reduction in mid-span displacement.

4. Conclusions

The results show that different TMD schemes used in this study are not robust against uncertainties in ground motion characteristics. While some of the TMD schemes can provide response reduction of up to 25% when subjected to a few of the 100 ground motions considered here, they are ineffective in many of these ground motions, and have adverse effects in some cases. This highlights the problem that passive devices such as TMDs are sensitive to the characteristics of ground motions. A structure, during its useful life, may be subject to different types of ground motions. Any vibration control scheme, to be effective, needs to be robust and advantageous in the most likely and demanding ground motion the structure might face. It is therefore important to study the influence of ground motion characteristics on performance of TMDs by considering a wide range of possible ground motions, rather than making conclusions based on a few selected ground motions, which can be misleading. In a more specific situation, where hazard deaggregation or other knowledge of potential ground motion allows an analyst to constrain the range of ground motions relevant for the structure being designed, the TMDs may be optimized to those expected ground motion scenarios. In more general studies of effectiveness of TMDs in seismic response mitigation of structures, conclusions based on a few selected ground motions can be misleading, and therefore results from the published literature making use of a few selected ground motions should be interpreted with caution.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

5. Author Contributions

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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7. Data Availability Statement

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

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