



Seismic Response of Building Structures with Sliding Non-structural Elements

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ABSTRACT

Interaction between a structure under base excitation and heavy non-structural elements that it supports is significant in the seismic analysis and design of the structure. Heavy non-structural elements may slide/rock under base excitation, and this dynamic action affects the seismic behavior of the supporting structure. Hence, in this study, a numerical model was presented to describe the seismic behavior of a primary structure (PS) supporting non-structural elements referred to as secondary bodies (SBs). The governing equations of motion for PS and SBs were developed considering Coulomb's friction model. Seismic hazard levels corresponding to Indian seismic zone III (medium hazard level) and V (highest hazard level) were considered. A parameter called *displacement ratio (DR)* was defined to quantify the sliding effect of SBs on the displacement response of the PS. A parametric study has been conducted to understand the variation in the *DR* due to varied time period of the structure, live loads to structure mass ratios and coefficients of friction between PS and SBs. From the analysis of results, it was concluded that the *DR* varies significantly with the time period, mass ratios, and coefficient of friction values. It can also be found from the study that the energy dissipation due to sliding of SBs was more in the highest hazard level than medium hazard level. Finally, the conditions for which the full mass of sliding secondary bodies should be considered in the seismic design of the structure are also presented.

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NOMENCLATURE

PS	Primary structure	T_p	Structural period (s)
SBs	Secondary bodies	k	Lateral stiffness of the Primary structure (N/m)
DR	Displacement Ratio	c	Damping coefficient (N-s/m)
m_p	Mass of the Primary structure (kg)	Greek Symbols	
m_{bi}	Mass of the i th secondary body (kg)	μ_{si}	Static coefficient of friction between PS and i th SB
u_g	Ground displacement (m)	μ_{ki}	Kinematic coefficient of friction between PS and i th SB
u_p	Displacement of the Primary structure (m)	α_i	Mass ratio of the i th secondary body
u_{bi}	Displacement of the i th Secondary body (m)		

1. INTRODUCTION

Damage to non-structural elements (NSEs) can occur even at low levels of ground shaking [1]. Non-structural elements whose anchorage mechanism is not proper or with no anchorages are more vulnerable to earthquakes [2, 3]. Sliding of such NSEs can result in economic loss and injury. The literature on these types of NSEs ranges from the closed-form and numerical solutions describing the sliding displacement of NSEs under base excitations

[4-6]. Sliding of heavy NSEs may affect the structural response of the structure, and hence their interaction must be considered [7]. Sliding displacements of elements are very sensitive to the coefficient of friction [8]. The reduction in the displacement of the structure with sliding live load during seismic events has been confirmed in the previous studies [9-11]. In the event of a major earthquake, the NSEs will slide when the inertial force of the load exceeds the friction force, and some part of the seismic energy of the structure is dissipated by the

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friction. Although the sliding of these elements is not commonly considered in structural design, consideration of sliding may reduce the portion of the live load that should be considered [11]. However, the above studies derived conclusions based on single sliding live loads on the supporting structure for a given seismic hazard level. But in reality, there exist multiple sliding live loads on the supporting structure. The dynamic behavior of a structure will be very different with multiple sliding bodies on it. Containers used for storage in pile-supported structures, heavy leads blankets draped on scaffolding structure in the nuclear industry, critical and sensitive laboratory equipment, spent nuclear fuel storage casks, etc., are few examples of such objects. Therefore, it is important to study multiple loads sliding on the seismic response of the supporting structure.

In response to the previous research limited to a single sliding rigid block, this paper presents the theoretical background and numerical model to depict the dynamic interaction between a multiple sliding rigid blocks and its supporting single-degree of freedom (SDOF) primary structure. The seismic response of the structure is obtained by varying the structural period, mass ratios, and coefficient of friction values for a given seismic hazard level. An overview of the steps of the research methodology is illustrated in Figure 1.

The organization of the paper is as follows: Section 2 describes the problem statement. Section 3 presents the numerical model and the governing equations of motion. Sections 4 and 5 present the details of the earthquakes and results for validating the present study with the existing study, respectively. Sections 6 and 7 present the analysis and parametric study results. Concise conclusions are drawn in the last section (i.e., Section 8).

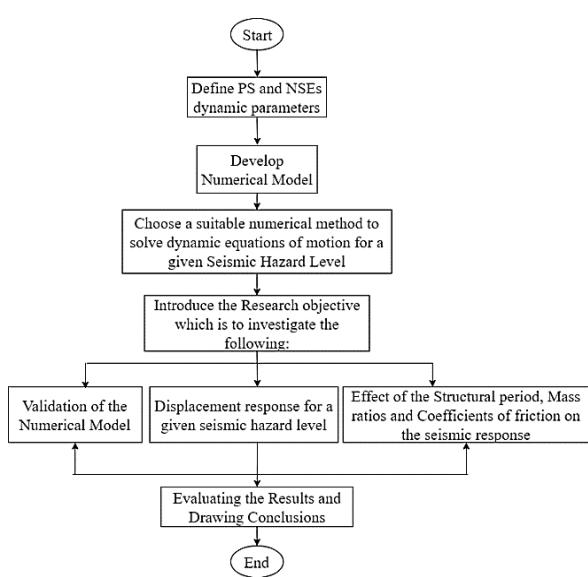


Figure 1. Flow chart of Research Methodology

2. PROBLEM STATEMENT

In this study, the seismic behavior of an SDOF primary structure with multiple sliding live load objects is investigated under real earthquake excitations. Spectrum compatible ground motions are used in the analysis of the SDOF structure with SBs. The equations governing the motion of primary and secondary masses are developed considering Coulomb's friction model [12]. The equations were solved by the 4th order Runge-Kutta method. The following are the assumptions made in this study:

- The single-degree primary structure is linearly elastic.
- Static and kinematic coefficients of friction are equal in magnitude.
- Live load objects are sufficiently squat as to slide but not rock.
- Live load objects are far enough from each other and other obstructions as to not cause impact collision between them.

3. NUMERICAL MODEL

A single-degree primary structure (PS) with mass m_p , lateral stiffness k and viscous damping c with multiple secondary bodies is considered. Figure 2 shows the structure with secondary bodies. Let μ_{si} and μ_{ki} be the static and kinematic coefficients of friction between the structure (m_p) and the i^{th} secondary body (m_{bi}). Static and kinematic coefficients of friction are assumed as equal in this study ($\mu_{si} = \mu_{ki}$, say μ_i). The displacements of the primary structure, i^{th} secondary body and the ground are defined as u_p , u_{bi} and u_g respectively. The dynamic equations of motion for the system can be written as follows:

A function **stick** is defined as shown in Equation (1) to check the stick/slip behavior between the bodies.

$$\text{stick}(u_g, u_p, u_b, \mu_s) = (|\ddot{u}_p + \dot{u}_g| < \mu_s g) \quad \& \quad (\dot{u}_p = \dot{u}_b) \quad (1)$$

If **stick** = 1 (True), then the secondary body sticks to the primary structure.

= 0 (False), the body slides (μ_k is active)

Note that **stick'** is the slip condition. Let n be the number of secondary bodies placed on the primary structure. The dynamic equations of motion are derived as follows:

For the primary structure

$$\begin{aligned} & [\{m_p + \sum_{j=1}^n m_{bj} \text{ stick}(u_g, u_p, u_{bj}, \mu_{sj})\}(\ddot{u}_p + \\ & \ddot{u}_g)] + c\dot{u}_p + ku_p = \\ & \sum_{i=1}^n \text{ stick}'(u_g, u_p, u_{bi}, \mu_{si}) \mu_{ki} m_{bi} g \\ & . \text{sign}(\dot{u}_{bi} - \dot{u}_p) \end{aligned} \quad (2)$$

sign is the mathematical signum function, which equals to +1 if the relative velocity ($\dot{u}_{bi} - \dot{u}_p$) is positive, -1 if the relative velocity ($\dot{u}_{bi} - \dot{u}_p$) is negative, or zero if relative velocity ($\dot{u}_{bi} - \dot{u}_p$) = 0.

For all the sliding secondary bodies (only when $\text{stick}(u_g, u_p, u_{bi}, \mu_{si}) = 0$

$$m_{bi}(\ddot{u}_{bi} + \ddot{u}_g) + \mu_{ki}m_{bi}g.\text{sign}(\dot{u}_{bi} - \dot{u}_p) \quad (3)$$

It should be noted that if I bodies are sliding, the total number of equations to be solved are $I+1$ (Equations (2) and (3)). The above governing dynamic equations of motion of PS and SBs in stick and slip mode are solved by the 4th order Runge-Kutta method. In subsequent discussions, the mass ratio (α_i) and original structural period (T_p) are introduced and defined as shown in Equations (4) and (5):

$$\text{, } \forall i = 1 \text{ to } n \text{ } \alpha_i = \frac{m_{bi}}{m_p} \quad (4)$$

$$T_p = 2\pi \sqrt{\frac{m_p}{k}} \quad (5)$$

4. SELECTION OF STRONG GROUND MOTIONS

In order to capture the effect of sliding bodies on the dynamic behavior of a structure, 11 earthquake excitations were selected from the PEER NGA WEST2 ground motion database [13] which is the minimum required number of ground motions as per ASCE 7-16 [14]. The moment magnitude (M_w) of the selected excitations is greater than 6. Excitations are made compatible with the design spectrum associated with seismic zones III and V, hard soil with 5% damping by the spectral matching method in the time domain. The details of the excitations are shown in Table 1. Figure 3 shows the IS 1893:2016 [15] design spectra as a target spectrum associated with 5% damping.

Figure 4 shows the 5%-damping mean response spectrum of the 11 earthquake excitations. The average

spectrum or mean spectrum does not fall below 90% of the target spectrum in the entire period range as per ASCE 7-16.

5. VALIDATION OF THE STUDY

It is necessary to verify the numerical model before conducting further studies.

The validation of the numerical model in this study is done by comparing the velocity responses of the PS and rigid block obtained in this study with the velocity responses of the supporting structure and rigid block obtained by the Nigam-Jennings method based on the

TABLE 1. Specifications of strong ground motions used in the current study

No.	Event	Year	Station	PGA (g)	Magnitude (M_w)
1	Kern County	1952	Taft Lincoln School	0.18	7.36
2	Loma Prieta	1989	Fremont-Mission San Jose	0.12	6.93
3	Landers	1992	Barstow	0.13	7.28
4	Duzce-Turkey	1999	Lamont 1059	0.15	7.14
5	Chi-Chi	1999	TCU075	0.22	6.21
6	Chi-Chi	1999	CHY028	0.20	6.20
7	Chi-Chi	1999	CHY046	0.12	6.22
8	San Simeon	2003	San Luis Obispo	0.16	6.52
9	Parkfield	1966	Cholame-Shandon Array #12	0.06	6.19
10	Iwate	2008	Semine Kurihara city	0.16	6.91
11	Parkfield	1966	Tembloar pre-1969	0.35	6.19

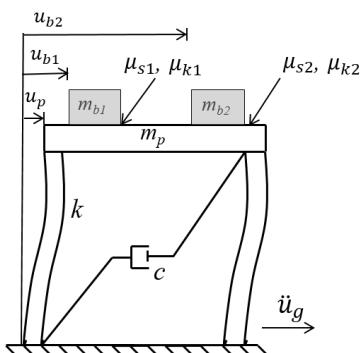


Figure 2. The idealization of single-degree primary structure with two SBs

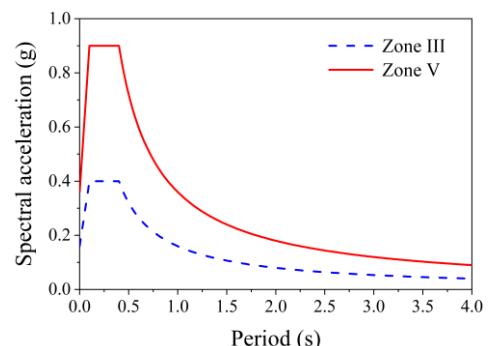


Figure 3. IS 1893:2016 Zone III and Zone V design spectra for hard soil

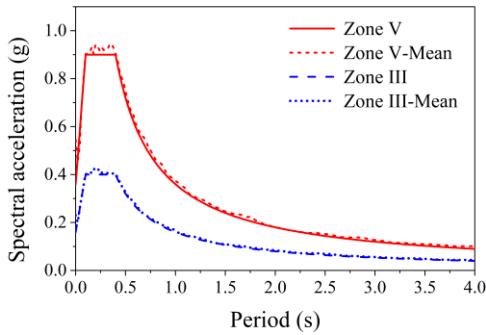


Figure 4. Target and mean acceleration spectra for 5% damping

exact solutions reported in literature [16]. Hence, the primary structure (m_p) with a single sliding rigid block (m_{b1}) is considered. The velocity responses of the structure and rigid block are plotted for stick-slip, stick-slip, and slip-slip conditions. For validating the numerical model, the slip-slip condition is arbitrarily chosen. The dynamic structural properties, rigid block parameters, and forcing function parameters used for the slip-slip mode in the literature [16] are given as input parameters to the numerical model in this study. Figure 5 shows an acceptable correspondence between this study and the velocity responses reported in literature [16] for slip-slip mode.

6. DISPLACEMENT RESPONSE

Previous research studies confirm the effect of a single sliding rigid block on the seismic response of the supporting structure. This study tries to investigate the

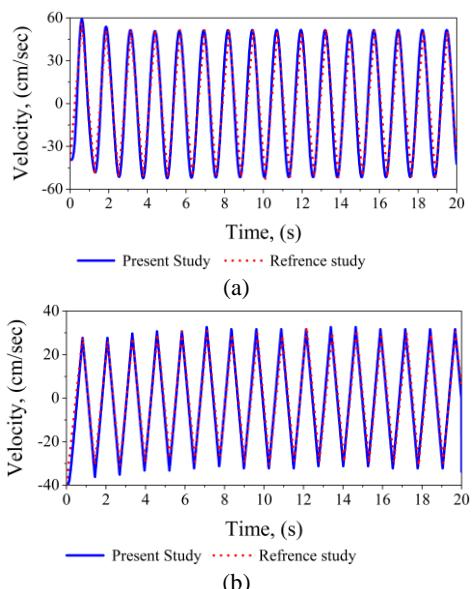


Figure 5. Velocity responses (a) primary structure (b) rigid block

The structural period of the PS is chosen as 0.5 s. In the case of PS with multiple SBs, the mass ratios (α_1 and α_2) are 0.5 and 0.5. The coefficients of friction (μ_1 and μ_2) are 0.3 and 0.1. The mass ratio and coefficient of friction in the case of PS with single SB are 1 and 0.3, respectively. Earthquake excitation-#11 from Table I is applied to the base of the PS with single and two SBs.

Figure 6 shows the displacement time histories of the PS with single and multiple SBs. Since the maximum displacement of the PS is of great concern for the design of the structures, maximum displacements of PS with single and two SBs for a given excitation corresponds to seismic zone III are 0.028 m and 0.021 m, respectively. For seismic zone V, those values are 0.044 m and 0.039 m. The maximum displacement of the PS with two SBs is reduced by 25% in zone III, and 11.36 % in zone V compared to PS with single SB, respectively.

Hence seismic behavior of the PS with multiple sliding rigid blocks is different from the structure with a single sliding rigid block. Similarly, Figure 7 shows the displacement time history of the PS with single and multiple SBs with the same coefficients of friction ($\mu_1 = \mu_2 = 0.1$) between the structure-SBs interfaces. From Figure 7, it can be concluded that PS with two SBs is dynamically similar to the PS with single SB when the coefficients of friction are the same.

This conclusion leads to a further discussion on the response of the PS with multiple sliding rigid blocks. In order to verify the effect of seismic hazard level on the response of the PS with multiple SBs, the effect of two rigid sliding blocks (m_{b1} and m_{b2}) on the displacement response of the primary structure in two seismic zones

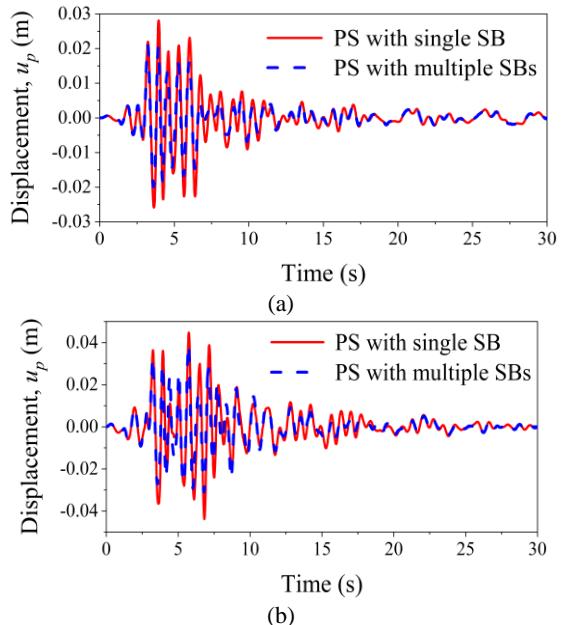


Figure 6. Displacement of PS with single and two SBs (a) Zone III (b) Zone V

III and V are studied. One ground motion from each seismic hazard level is applied to the PS with SBs. The structural period of the PS is arbitrarily chosen as 0.8 s. Mass ratios (α_1 and α_2) are chosen as 0.5. Coefficients of friction (μ_1 and μ_2) are chosen as 0.2 and 0.1 between the blocks and structure interface.

The displacement response of the structure with sliding loads ($(u_p)_{sliding}$) is compared against the response of the same structure with rigidly fixed SBs ($(u_p)_{rigid}$). From Figure 8, it can be deduced that sliding live loads can mitigate the seismic response of the primary structure when compared to PS with rigidly

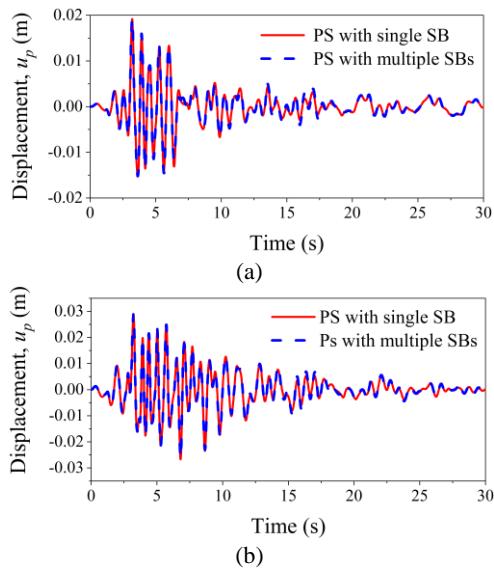


Figure 7. Displacement of PS for same coefficients of friction (a) Zone III (b) Zone V

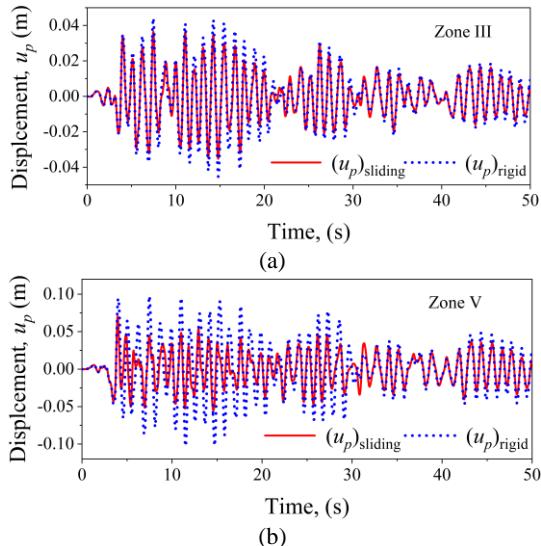


Figure 8. Displacement of primary structure (a) Zone III (b) Zone V

attached SBs. The reduction in displacement is more in zone V (31.4%) compared to zone III (17.3%). This is because acceleration experienced by the structure is more in zone V, which overcome the static friction between block-structure interface, and hence sliding of the SBs is higher. Due to the higher sliding of SBs, more energy is dissipated in the highest seismic hazard level when compared to the medium seismic hazard level.

7. PARAMETRIC STUDY

The numerical model was used to evaluate the seismic response of the single-story primary structure. A parametric study has been conducted by changing the parameters: (1) structural period, (2) the blocks-to-structure mass ratio, (3) the coefficient of friction at the interface of the blocks and structure. Viscous damping ratio was taken as 5% of the critical damping of the primary structure. In this study, a parameter called *displacement ratio* (DR) is introduced as shown in Equation (6) to quantify the effect of sliding live loads on the seismic response of the primary structure since drift is the widely accepted parameter due to its accepted correlation with structural and non-structural damage [10, 17]. It is calculated as follows:

$$DR = \frac{(u_p)_{sliding} - (u_p)_{free}}{(u_p)_{rigid} - (u_p)_{free}} \quad (6)$$

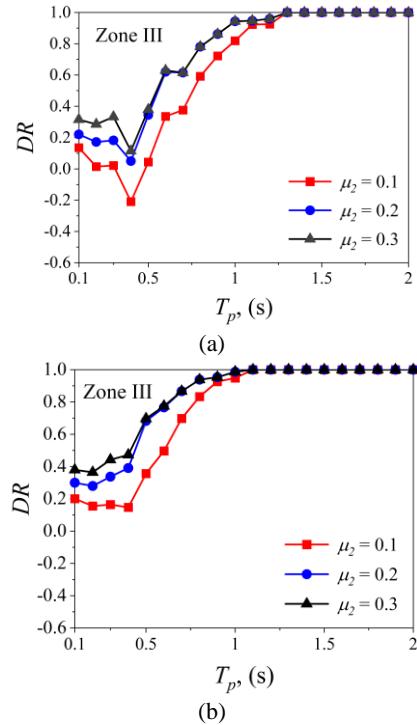


Figure 9. Displacement Ratio (DR) for zone III, $\mu_1 = 0.1$
(a) $\alpha_1 = \alpha_2 = 0.5$; (b) $\alpha_1 = \alpha_2 = 1$

$(u_p)_{sliding}$ is the displacement of the PS with sliding live loads. $(u_p)_{rigid}$ and $(u_p)_{free}$ are the displacements of the same structure with rigidly fixed SBs and with no SBs respectively. In every case, displacement was defined as the mean value of the maximum displacements obtained for an array of eleven scaled ground motions corresponding to each seismic hazard level. A DR equal to one indicates that SBs behave as rigidly attached bodies to the PS. The effect of sliding live loads on the seismic response of the structure is negligible when DR is close to zero. The rigid sliding blocks mitigate the response of the primary structure if DR is negative. If DR varies between 0 and 1, only some portion of the mass of SBs has to be considered in the seismic analysis of the PS.

Figure 9 summarizes the results for the displacement ratio (DR) for medium seismic hazard level (zone III). It can be observed that DR varies significantly with the structural period, coefficient of friction, and mass ratios. This behavior agrees with the conclusion reported in literature [18]. A practical implication that can be drawn from Figure 9 is that sliding rigid blocks on structures with $T_p > 1.3$ s could behave as rigidly attached to the PS since $DR = 1$ regardless of the blocks-to-structure mass ratios. As observed from Figure 9a, DR decreases for structures with periods less than or equal to 0.4 s. This is because ground acceleration increases with the structural period up to 0.4 s as observed from the given spectra (Figure 3), and hence they overcome the static friction, and sliding of SBs takes place. For structures with $T_p > 0.4$ s, DR increases significantly with coefficients of friction since ground acceleration decreases with T_p . For higher mass ratios, the decreases in DR is very minimal and increases significantly with structural period and coefficient of friction values (Figure 9b). For a given seismic hazard level, an increase in mass ratio results in an increase in limiting static frictional force between the interfaces of the PS and SBs. Due to this, an effective period of the structure-SBs system increases, which results in the lower accelerations that are insufficient to overcome the friction between the SBs and PS. Hence, higher mass ratios are significant on the seismic response of the PS. DR is positive for higher mass ratios even for the small coefficient of friction and hence some portion of SBs participates in the inertia of the PS as shown in Figure 9b. This behavior is observed in the literature [19].

Figure 10 presents the results for the displacement ratio (DR) for the highest seismic hazard level (zone V). Figure 10 shows that also for the highest seismic hazard zone, the DR significantly decreases for structures with periods less than or equal to 0.4 s for lower mass ratios. For higher mass ratios, DR increases significantly with structural period and coefficients of friction values. From Figures 9 and 10, it can be observed that DR values in zone V are less than the values in the zone III for the given input parameters.

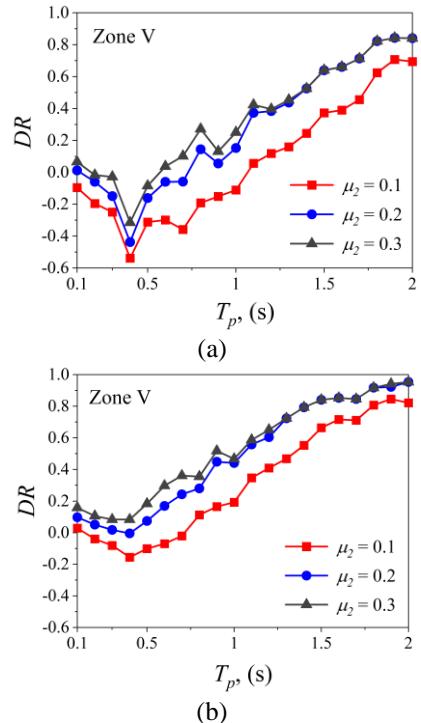


Figure 10. Displacement Ratio (DR) for zone V, $\mu_1 = 0.1$
(a) $\alpha_1 = \alpha_2 = 0.5$; (b) $\alpha_1 = \alpha_2 = 1$

This is because, zone V is the highest seismic hazard zone, the accelerations experienced by the structure are more which in turn increases the sliding of the SBs. The full mass of the rigid sliding blocks cannot be considered for any structure under highest seismic hazard level since DR is not equal to one.

8. CONCLUSIONS

The objective of this paper is to study the effect of multiple live load objects on the seismic behavior of the primary structure. A numerical model that describes the response of the SDOF structure supporting two rigid blocks with a possibility to slide was developed. The governing equations of motion were derived and solved by the fourth-order Runge-Kutta method. Spectrum compatible ground motions are applied to the structure with live load objects. From the present study, it can be concluded that the seismic behavior of the primary structure is significantly affected by the sliding live load objects under real earthquake ground motions. Structures with a single sliding block is dynamically similar to structures with multiple sliding rigid blocks when the coefficients of friction are the same. Under both medium and highest seismic hazard levels, the response of the structure with periods longer than 0.4 s increases significantly with structural period and coefficients of friction values for lower mass ratios. For structures with

periods less than or equal to 0.4 s, the response of the structure decreases with structural period. The seismic response of the structure increases significantly with structural period and coefficients of friction for higher mass ratios under both medium and highest seismic hazard levels. For medium seismic hazard level, sliding bodies behave as a rigidly attached bodies to the primary structure with $T_p > 1.3$ s for a given set of mass ratios and coefficient of friction values. Hence the full mass of the sliding bodies has to be considered in the seismic analysis of PS. For a given mass ratios and coefficient of friction values, only some portion of the mass of sliding bodies has to be considered for any structure under the highest seismic hazard level.

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Seismic Hazard Level

یکی از موارد اثرگذار در تحلیل و طراحی لرزه ای سازه ها اندرکنش میان تحریک پایه و اجزای سنتگین موجود در ساختمان می باشد. این مطالعه به ارائه مدلی به منظور توصیف رفتار لرزه ای یک سازه اصلی که بایستی وزن المانهای فرعی با قابلیت لغزش را تحمل نماید می پردازد. معادلات دینامیکی حرکت مربوط به سازه اصلی و فرعی توسط مدل اصطکاکی کلمب توسعه داده شده اند. سطوح خطر مورد بررسی در این مطالعه بر مبنای سطوح خطر ۳ و ۴ در آینه نامه طراحی لرزه ای هند می باشد. پارامتری جدید تحت عنوان نسبت جابجایی توسط محققین تعریف گردیده تا اثر المان فرعی لغزش را بر پاسخ جابجایی سیستم محاسبه نماید. یک تحلیل پارامتریک به منظور ارزیابی نوسانات نسبت جابجایی در اثر دوره تنابوب سازه، بارهای زنده و ضریب اصطکاک بین سازه اصلی و المان فرعی نیز صورت پذیرفته است. بر مبنای نتایج تحلیل حساسیت، محققین به این جمع بندی رسیدند که شاخص نسبت جابجایی تعریف شده در این مطالعه به طور قابل توجهی با دوره تنابوب سازه، نسبت بار زنده به جرم و ضرایب اصطکاک افزایش می یابد. در نهایت شرایطی که می توان تحت آنها از اثر لغزش بین دو سازه در طراحی لرزه ای چشم پوشی کرد ارائه گردیده است.

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