17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

SEISMIC RESPONSE OF STRUCTURES WITH STACKED AND SLIDING LIVE LOADS

C.Parimi[(1)], S.P.Challagulla[(2)]

[(1)] *Assistant Professor, Department of Civil Engineering, BITS-Pilani, Hyderabad, India, parimi@hyderabad.bits-pilani.ac.in*
[(2)] *Research Scholar, Department of Civil Engineering, BITS-Pilani, Hyderabad, India, p20150407@hyderabad.bits-pilani.ac.in*

Abstract

Heavy components resting on a structure are usually considered to be part of live loads in the design of the structure. Guidelines suggest different percentages of the live loads as masses in the main structure inertia. A close look at these guidelines is required to understand these inertial masses better. Assuming these components to be rigidly attached to the main structure, the design of the structure becomes too conservative since energy dissipation due to friction between their interfaces is neglected. On the other hand, the design can be unsafe if these components are completely neglected in horizontal excitation. This paper proposes a generalized study on the effect of sliding live loads on the seismic response of the main structure. The complexity in the problem arises when the live loads are due to stacked objects. Such stacks are widely seen in docks and storage structures. In these cases, energy dissipation by friction will be seen between various layers of the stack and also between the main structure and the live load objects. This paper studies such stacked live loads considering sliding between various layers and of the whole stack. Slip, Stick and Stick-Slip phenomenon will be present between various levels of stacks depending on the excitation and frictional properties. While some work has been done on the seismic behavior of main structure with single live load object, studies on stacked live load objects are needed.

In this paper a stack (one on the top of the other) of two sliding rigid bodies is considered. The main structure is termed as primary structure (PS) and stacked live load objects are considered as secondary bodies (SBs). The lower secondary body (SB_1) interacts with the PS through friction. Such friction is also present between the two SBs of the stack. The equations governing the motion of PS and SBs are developed considering Coulomb's friction model and are solved using 4^{th} order Runge-Kutta method. Spectrum compatible ground motions associated with the two Indian seismic hazard levels consistent with medium and highest conditions were considered. The model is validated by comparing it to single live load object model from literature with various combinations. An extensive parametric study has been presented to show the variation of displacement of the PS as a function of **i)** the fundamental period of the structure, **ii)** the live load (SB_1 and SB_2) to structure mass ratio, **iii)** the friction coefficient between SB_1 and PS, **iv)** the friction coefficient between SB_1 and SB_2. From the analysis, it was observed that the seismic response of the PS with a two-level stack of live load objects is different from the response of a PS with a single sliding live load object. It was also observed that displacement estimates are conservative by neglecting energy dissipation associated to the relative movement of live load objects in the stack. The conditions for which the entire live load objects should be considered as inertia in the seismic design of structures are also presented.

Keywords: Primary structure; Secondary bodies; Coulomb friction; Sliding; Stacked live load.

1. Introduction

Earthquake resistant design of structures involves the calculation of seismic forces as the summation of dead and live loads. Self-weight of the structure can be calculated trivially, but the calculation of live loads is not as easy. Design standards provide limited guidance on how to include them in the structural analysis. Percentages suggested by design standards do not show a mechanical basis and assume that only a fraction of the live load mass is present during a seismic event. However, pile supported storage structures and scaffolding structures with lead blankets are structures with nearly permanent live loads. Therefore, the live loads are to be considered fully and not as a small percentage of dead loads. Seismic design in these cases becomes conservative since the live loads might not fully participate in the dynamics of the structure. Further, the design of the structure becomes unsafe if live loads are totally ignored. Sliding of live loads is caused by poor anchorage mechanisms when the supporting structure is subjected to external excitation. Due to these sliding live loads, some of the input energy dissipates through friction and only a some portions of the mass of live loads are effective as seismic weight [1].

The behavior of sliding rigid blocks under base excitation is a complex problem of dynamics that has been studied extensively for many decades. The effect of base excitation frequency on the stability of rigid blocks was widely studied [2, 3]. The sliding displacement of the unanchored body depends on the earthquake intensity and coefficients of friction [4-6]. The effect of near-fault ground motions on the sliding systems was studied [7]. The authors conclude that the effect of a strong vertical component of a ground motion on the slippage was not remarkable.A study [8] presents the effect of stick-slip phenomenon on the sliding response of objects under pulse excitation. It concluded that the peak sliding displacement is mainly controlled by kinematic friction. An experimental study was conducted on the sliding response of a free standing rack [9] and the results demonstrated that the sliding displacement was larger with seismic waves in a long-period range.

Contrary to extensive research on the seismic response of rigid blocks or free standing structures under base excitation, some studies have focused on the dynamic interaction between rigid blocks and their supporting structures. A study [10] examines the seismic response of a rectangular sliding rigid block on the structure with linear spring and a dashpot and concludes that the slippage increases when the mass of structure was small relative to that of the block. The response of an oscillator with a sliding load system is influenced by mass ratio and friction coefficient [11]. Effect of live load on the dynamic response of structures is studied and the ratio of structure's drift when the live loads are flexibly connected to the primary system to the structure's drift when the live load objects are rigidly attached was reported [12]. The authors developed a finite element (FE) model of the structure with a sliding rigid block [13]. They claim that the FE model is useful for conducting some parametric studies that are useful for design regulations. A design expression has been developed that allows the estimation of the portion of live load to be included in the primary structural inertia [14]. Design expression [14] proposed by the authors in the study was validated against shake table tests [15]. Recently, the effect of sliding rigid blocks on the seismic behavior of multi degree of freedom (MDF) system has also been studied [16]. The authors conducted a parametric study to quantify the effective portion of live load mass that contributes to the seismic weight.

The above studies are limited to the effect of a single sliding mass on the seismic response of a structure. The problem becomes more complex when the live loads consist of stacked objects. Such stacks are widely found in docks and storage structures. In these cases, energy dissipation by friction will be seen between various layers of the stack and also between the supporting structure and the live load objects. By ignoring the energy dissipation due to friction between the live load objects in the stack, the response of the structure can be overestimated by treating the live load as one single object.

This study considers a two-level stacked body (one above the other) as the live load. This paper presents a numerical model to describe the dynamic interaction between different levels of the stack and between the stack and the structure. A parametric study was performed to show the variation in the displacement response of the structure to a given seismic hazard level.

The organization of the paper is as follows: Section 2 describes a numerical model. Section 3 presents the details of the earthquakes. Sections 4 shows the results to validate the present study with an existing study. Sections 5 presents the results of the parametric study. Brief conclusions are drawn in the last section (i.e., Section 6).

2. Numerical Model

Linear elastic single-degree-of-freedom (SDOF) primary structure (PS) with mass m_p, lateral stiffness k, and damping coefficient c supports two level stack of sliding secondary bodies (SBs). The lower body is represented as SB_1 with mass m_{b1} and top most body in the stack is represented as SB_2 with mass m_{b2}. Secondary body (SB_1) interacts with the PS through Coulomb friction. Such friction is also present between the two SBs of the stack. The static and kinetic coefficients of friction are represented as μ_s and μ_k, respectively. Let μ_{s1} and μ_{k1} are the frictional coefficients between m_p and m_{b1}, whereas μ_{s2} and μ_{k2} are the frictional coefficients between m_{b1} and m_{b2} respectively. In this study both the coefficients of friction are assumed as equal. The blocks are sufficiently squat so they can slide but does not show any rocking behavior.

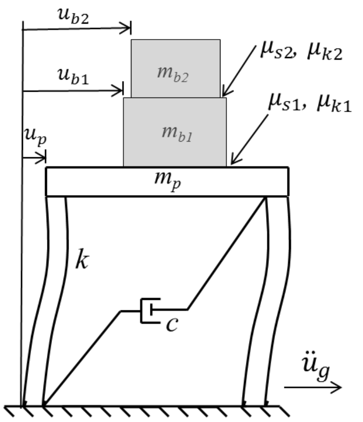


Fig.1 Idealization of SDOF structure with stack of SBs

Let u_p, u_{b1} and u_{b2} are the displacements of PS and SBs respectively with respect to ground. The combined system (PS+SBs) subjected to a ground acceleration, $\ddot{u}_g$. The dynamic equations of equilibrium for the combined system can be written as:

The blocks are attached to the PS and said to be in stick phase, it is $\dot{u}_p = \dot{u}_{b1} = \dot{u}_{b2}$ and following inequality should be valid:

$$\left|\ddot{u}_p + \ddot{u}_g\right| < \mu_{s1} g \quad \& \quad \left|\ddot{u}_{b1} + \ddot{u}_g\right| < \mu_{s2} g \tag{1}$$

The dynamic equilibrium of the PS results in the following:

$$(m_p + m_{b1} + m_{b2})(\ddot{u}_p + \ddot{u}_g) + c\dot{u}_p + ku_p = 0 \tag{2}$$

During sliding phase:

When the SB_1 is said to be in sliding phase and SB_2 is rigidly attached to the SB_1, the following inequality should be valid:

$$\left|\ddot{u}_p + \ddot{u}_g\right| \geq \mu_{s1} g \quad \& \quad \left|\ddot{u}_{b1} + \ddot{u}_g\right| < \mu_{s2} g \tag{3}$$

The dynamic equilibrium of the PS and SB_1 results in the following:

$$m_p(\ddot{u}_p + \ddot{u}_g) + c\dot{u}_p + ku_p = \mu_{k1}(m_{b1} + m_{b2})g\, sign(\dot{u}_{b1} - \dot{u}_p) \tag{4}$$

$$(m_{b1} + m_{b2})(\ddot{u}_{b1} + \ddot{u}_g) + \mu_{k1}(m_{b1} + m_{b2})g\, sign(\dot{u}_{b1} - \dot{u}_p) = 0 \tag{5}$$

The block SB_1 is reattached to the PS with the following condition:

$$\dot{u}_p = \dot{u}_{b1} \ \ \& \ \ |\ddot{u}_p + \ddot{u}_g| < \mu_{s1} g \tag{6}$$

When the SB_1 is said to be in stick phase and SB_2 is sliding with respect to the SB_1, the following inequality should be valid:

$$|\ddot{u}_p + \ddot{u}_g| < \mu_{s1}\left(\frac{m_{b2}}{m_{b1}}\right) g + \mu_{s1} g + \ \mu_{k2}\left(\frac{m_{b2}}{m_{b1}}\right) g \ sign(\dot{u}_{b2} - \dot{u}_{b1}) \ \ \& \ \ |\ddot{u}_{b1} + \ddot{u}_g| \geq \mu_{s2} g \tag{7}$$

The dynamic equilibrium of the PS and SB_2 results in the following:

$$(m_p + m_{b1})(\ddot{u}_p + \ddot{u}_g) + c\dot{u}_p + ku_p = \ \mu_{k2} m_{b2} g \ sign(\dot{u}_{b2} - \dot{u}_{b1}) \tag{8}$$

$$m_{b2}(\ddot{u}_{b2} + \ddot{u}_g) + \mu_{k2} m_{b2} g \ sign(\dot{u}_{b2} - \dot{u}_{b1}) = 0 \tag{9}$$

The block SB_2 is reattached to the SB_1 with the following condition:

$$\dot{u}_{b1} = \dot{u}_{b2} \ \ \& \ \ |\ddot{u}_{b1} + \ddot{u}_g| < \mu_{s2} g \tag{10}$$

The following inequality should be valid when the two SBs are in sliding phase:

$$|\ddot{u}_p + \ddot{u}_g| \geq \mu_{s1} g \ \ \& \ \ |\ddot{u}_{b1} + \ddot{u}_g| \geq \mu_{s2} g \tag{11}$$

The dynamic equilibrium of the PS, SB_1 and SB_2 results in the following:

$$m_p(\ddot{u}_p + \ddot{u}_g) + c\dot{u}_p + ku_p = \ \mu_{k1}(m_{b1} + m_{b2}) g \ sign(\dot{u}_{b1} - \dot{u}_p) \tag{12}$$

$$m_{b1}(\ddot{u}_{b1} + \ddot{u}_g) = -\mu_{k1}(m_{b1} + m_{b2}) g \ sign(\dot{u}_{b1} - \dot{u}_p) + \ \mu_{k2} m_{b2} g \ sign(\dot{u}_{b2} - \dot{u}_{b1}) \tag{13}$$

$$m_{b2}(\ddot{u}_{b2} + \ddot{u}_g) = -\mu_{k2} m_{b2} g \ sign(\dot{u}_{b2} - \dot{u}_{b1}) \tag{14}$$

The blocks SBs and PS are reattached with the following conditions:

$$\dot{u}_p = \dot{u}_{b1} = \dot{u}_{b2} \ \ \& \ \ |\ddot{u}_p + \ddot{u}_g| < \mu_{s1} g \ \ \& \ \ |\ddot{u}_{b1} + \ddot{u}_g| < \mu_{s2} g \tag{15}$$

The above governing dynamic equations of motion of PS and SBs in stick and sliding/slip mode are solved by 4th order Runge-Kutta method. In subsequent discussions, mass ratios (α_1 and α_2) of stack of live load objects, mass ratio (α) of single sliding live load object and original structural period (T_p) are introduced and defined as:

$$\alpha_1 = \frac{m_{b1}}{m_p} \tag{16}$$

$$\alpha_2 = \frac{m_{b2}}{m_p} \tag{17}$$

$$\alpha = (\alpha_1 + \ \alpha_2) \tag{18}$$

$$T_p = 2\pi\sqrt{\frac{m_p}{k}} \tag{19}$$

3. Selected Ground Motions

Two seismic scenarios namely medium (Zone III) and highest seismic hazard (Zone V) zones as per IS 1893:2016 [17] were considered in this study. The moment magnitude (M_w) of the selected excitations varies from 6.2 to 7.36 to represent wide range of magnitudes. Excitations were selected based upon the shear wave velocity (V_{S30}) of 360-760 m/s to represent hard soil condition as per NEHRP site classification system. Eleven ground motions were selected from the PEER NGA ground motion database [18] which is the minimum number for spectral matching technique as per ASCE/SEI 7-16 [19]. Excitations were spectrally matched to the corresponding hard soil response spectrum of the given seismic scenario by spectral matching method in time domain. The details of the excitations are shown in Table 1. Fig.2 shows the IS 1893:2016 target spectra associated with 5% damping. Fig.3 shows the 5%-damping mean response spectra 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.

Table 1. Details of Earthquake Excitations

S.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	6.2
6	Chi-Chi	1999	CHY028	0.20	6.2
7	Chi-Chi	1999	CHY046	0.12	6.2
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	6.9
11	Parkfield	1966	Temblor pre-1969	0.35	6.19

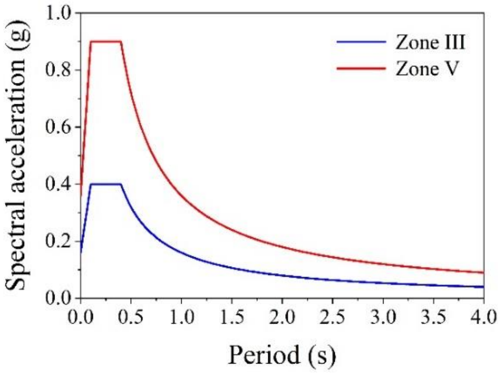


Fig.2 IS 1893:2016 Zone III and Zone V design spectra for hard soil

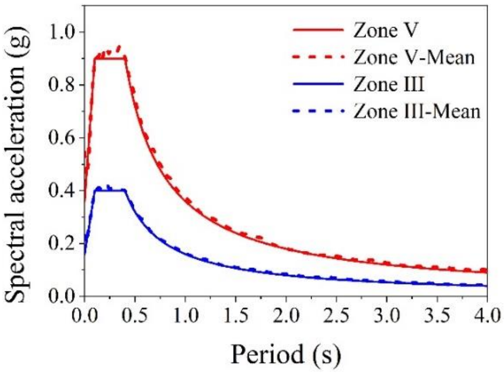
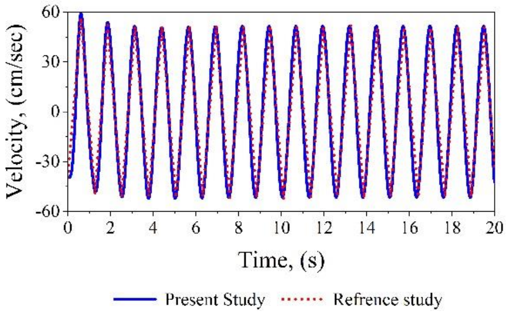


Fig.3 Target and mean acceleration spectra for 5% damping

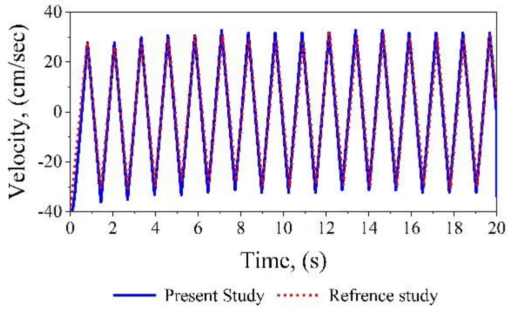
4. Validation of the Numerical Model

The numerical model should be verified before executing further studies. The validation of the numerical model was done by comparing the response of the structure and sliding bodies with the response of the structure with single sliding rigid block under harmonic excitation given in the reference study [2]. Since the model in the reference study was structure with single rigid block, upper body (SB_2) in the stack was rigidly attached to the lower body (SB_1) in the present study. The coefficients of friction between the bodies are varied such that the system will behave as a two body system, instead of a three bodies system. The slipping between all three masses are validated using this study.

The velocity responses were plotted for stick-stick, stick-slip, and slip-slip conditions in the reference study. In this paper validation was done only for slip-slip condition. The structural dynamic properties, rigid block interaction properties (mass ratio and coefficient of friction), and forcing function parameters were taken from the reference study. Fig.4 shows the acceptable correspondence between velocity responses obtained in this study with the reference study.



(a)



(b)

Fig.4 Velocity responses for: (a) Primary structure; (b) Rigid body

5. Parametric Study

The numerical model was used to investigate the influence of stack of live load objects on the seismic response of the primary structure. The variables included in the parametric study: (i) the fundamental period of the structure T_p (Eq. (19)); (ii) the blocks-to-structure mass ratios, α_1 and α_2 (Eq. (16) and Eq. (17)); (iii) the coefficient of friction at the interface of SBs ($\mu_2 = \mu_{s2} = \mu_{k2}$); SB_1 and PS ($\mu_1 = \mu_{s1} = \mu_{k1}$). Different analysis runs were analyzed as a result of different variable permutations for each seismic hazard zone. Each run involves the calculation of the mean of the maximum displacement response of the system for scaled eleven ground motions.

The parameter selected to quantify the effect of stack of SBs on the response of the primary structure in this study is Displacement Response Ratio (*DRR*). It is defined as follows:

$$DRR_1 = \frac{(u_p)_{stack}}{(u_p)_{rigid}}; \quad DRR_2 = \frac{(u_p)_{single}}{(u_p)_{rigid}} \tag{20}$$

Where, $(u_p)_{stack}$ is the displacement of a structure supporting the stack of SBs and $(u_p)_{single}$ is the displacement of the same structure but supporting a single sliding block ($\alpha = \alpha_1 + \alpha_2$). $(u_p)_{rigid}$ is the displacement of the structure supporting blocks that are rigidly attached. A DRR_1 or DRR_2 approaching one indicates that most of the blocks mass is attached to the PS. If the ratio of DRR_1 to DRR_2 approaching one, it indicates that most of the mass of upper block in the stack is attached to the lower block. It should be noted that coefficient of friction (μ) at the structure–block interface in the case of single block is equal to μ_1.

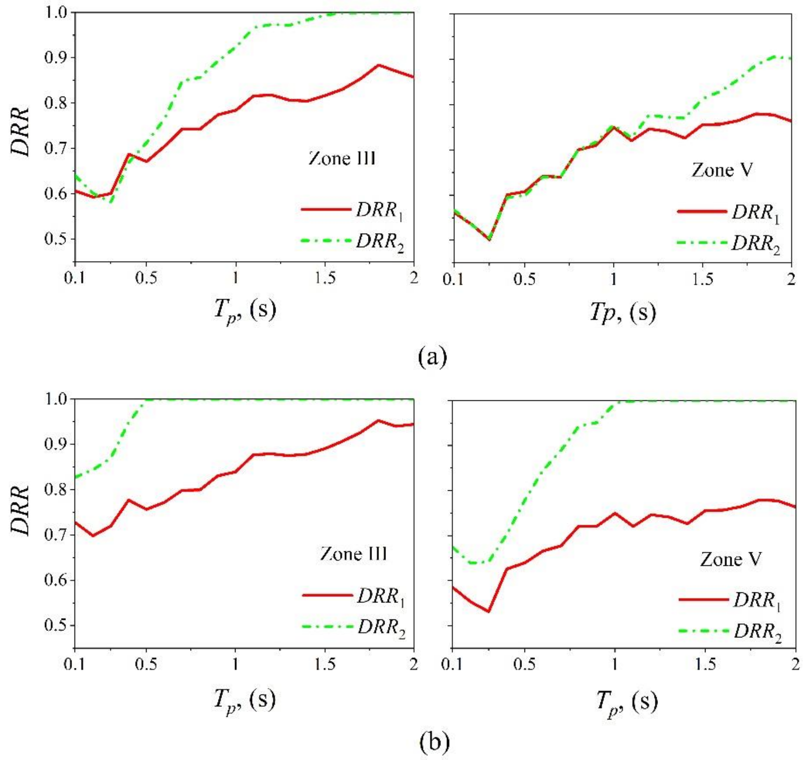


Fig.5 Displacement Response Ratio (DRR) for primary structure, α_1 = 0.25, α_2 = 0.25, α= 0.5, μ_2 = 0.05: (a) μ_1 = μ = 0.1; (b) μ_1 = μ = 0.3.

Fig.5 summarizes the results for the few cases showing the variation in DRR with respect to different structural periods and seismic zones to verify the effect of stack of sliding rigid blocks on the seismic response of the primary structure. It can be observed that DRR significantly increases with the period of the structure and coefficient of friction. It can also be observed that displacement estimates are conservative by neglecting energy dissipation associated to the relative movement between blocks since $DRR_2 > DRR_1$.

Fig.6 presents the results of a few cases of parametric study for the scaled records of the medium seismic hazard zone. As expected, values of DRR_1 and DRR_2 increase significantly with the period of the structure and the coefficient of friction, especially for larger values of mass ratio. An observation that can be drawn from Fig.6 is that if $\mu_2 \leq \mu_1$, input energy is dissipated by relative movement between the blocks ($DRR_1 < DRR_2$). If $\mu_2 > \mu_1$, no such energy dissipation was observed due to relative movement of the blocks ($DRR_1 = DRR_2$). DRR_1 and DRR_2 decrease with the blocks-to-structure mass ratios for $T_p < 1$s, but for longer time periods the influence of this parameter is less significant. This behavior can be attributed to the fact that for a given set of coefficients of friction values ($\mu_1$and μ_2), the accelerations are high for lower time period structures (stiff structures). The sliding displacement of the upper block (m_{b2}) increases with increase in mass ratios and hence more amount of energy is dissipated. It is also inferred from the Fig.6 that for structures with periods longer than 2.0s, rigid blocks would behave as rigidly attached bodies to the primary structure.

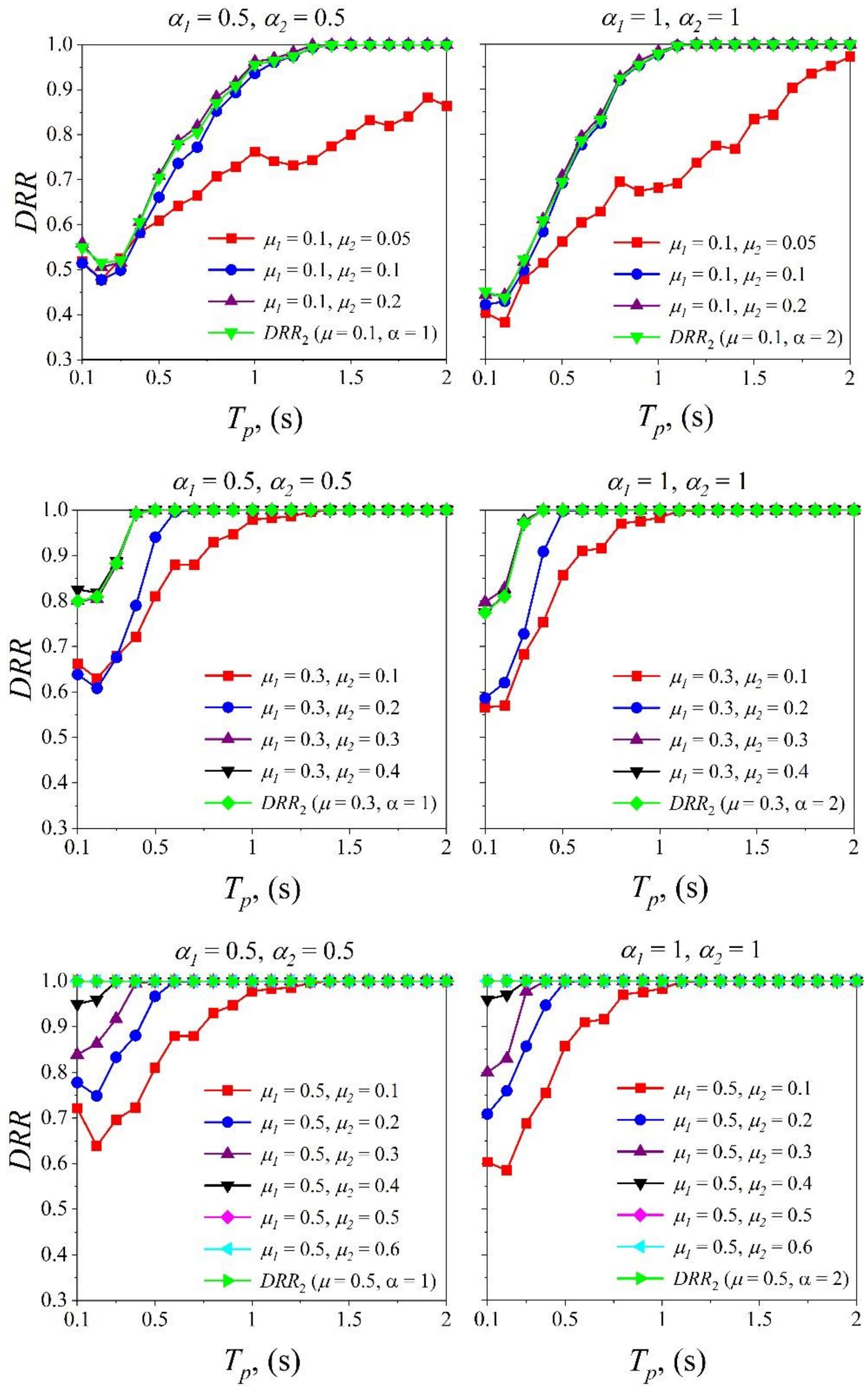


Figure 6. Displacement Response Ratio (*DRR*) for primary structure under medium seismic hazard zone (Zone III)

Fig.7 presents the results of the parametric study for scaled eleven records of the highest seismic hazard zone. Fig.7 confirms that also for highest seismic zone *DRR* increases significantly with the period of the structure and the coefficient of friction as stated earlier. Energy dissipation due to friction between stack of blocks is negligible when $\mu_2 > \mu_1$ in this case also. Hence from Figs. 6 and 7, it can be concluded that regardless of seismic hazard zone, mass ratios and friction coefficients if $\mu_2 > \mu_1$, a stack of rigid blocks can be considered as a single sliding rigid block. DRR decreases with the mass ratios for lower structural periods ($T_p < 1$ s) as seen before. This observtaion in this study coincides with the one of the conclusions drawn in studies [1, 12].

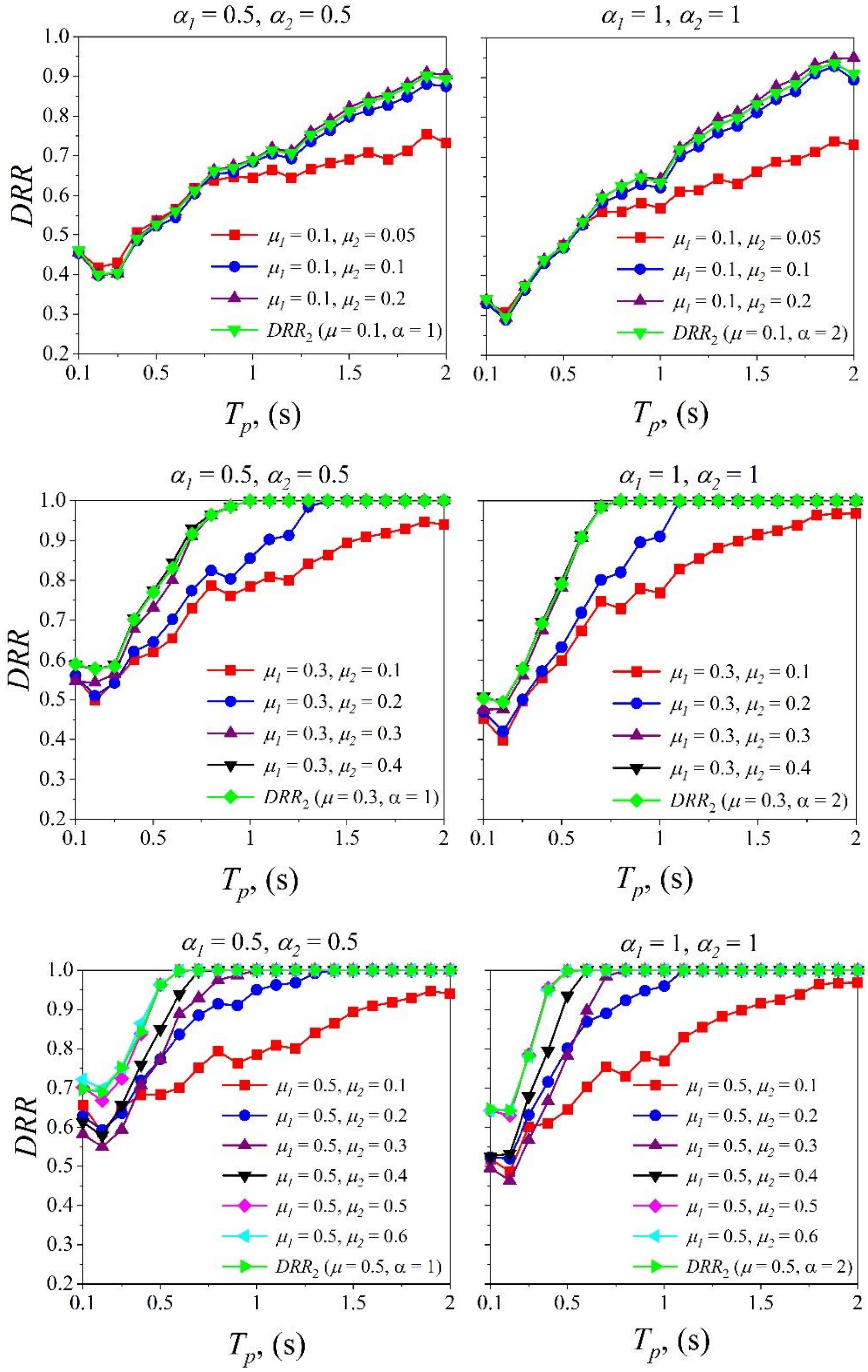


Figure 7. Displacement Response Ratio (DRR) for primary structure under highest seismic hazard zone (Zone V)

6. Summary and Conclusions

The main objective of this paper is to investigate the effect of live load stacks on the seismic behavior of the primary structure. A numerical model has been developed that describes the seismic behavior of the primary structure, which supports a two level stack of sliding rigid blocks. The governing equations of motion were derived for the primary structure and secondary bodies by considering Coulomb's friction model and were solved using 4th order Runge-Kutta method. Spectrum compatible ground motions were then applied to the structure with live load objects. An extensive parametric study was carried out to verify the effect of various parameters such as structural period, live load object-structure mass ratios and friction coefficients on the displacement response of the structure. This study reveals the following conclusions:

- Seismic response of a structure with a two-level stack of live load objects is different from the response of the same structure with a single sliding live load object under real earthquake excitations.
- The displacement estimates of the primary structure are found to be conservative by ignoring the energy dissipation associated to the relative movement of rigid blocks in the stack.
- Under both medium and highest seismic zones, the displacement response of the structure increases significantly with the structural period, mass ratios and coefficients of friction.
- Regardless of the seismic hazard zones, mass ratios and coefficients of friction, if $\mu_2 > \mu_1$, the energy associated to the relative movement of rigid blocks in the stack does not dissipate.
- For structures with $T_p \geq 2$s, live load objects would behave as a rigidly attached regardless of mass ratios and friction coefficients under medium seismic hazard zone, except for a very small coefficients of friction at the stack level ($\mu_2 = 0.05$).
- For structures with $T_p \geq 1.25$s, entire live load objects should be considered in the primary structure inertia for: (i) structure-live load objects with $\mu_1 \geq 0.1$, $\mu_2 \geq 0.1$ under medium seismic hazard zone; (ii) structure-live load objects with $\mu_1 \geq 0.3$, $\mu_2 \geq 0.2$ under highest seismic hazard zone.

7. References

[1] Smith-Pardo, J. P., Reyes, J. C., Ardila-Giraldo, O. A., Ardila-Bothia, L., & Villamizar-Gonzalez, J. N. (2014): Dynamic effect of sliding rigid blocks on the seismic response of structures. In *Second European Conference on Earthquake Engineering and Seismology*, Istanbul.

[2] Matsui, K., Iura, M., Sasaki, T., & Kosaka, I. (1991): Periodic response of a rigid block resting on a footing subjected to harmonic excitation. *Earthquake Engineering & Structural Dynamics*, *20*(7), 683-697.

[3] Saraswat, A., Reddy, G. R., Ghosh, A. K., & Ghosh, S. (2016): Effects of base excitation frequency on the stability of a freestanding rigid block. *Acta Mechanica*, *227*(3), 795-812.

[4] Choi, B., & Tung, C. D. (2002): Estimating sliding displacement of an unanchored body subjected to earthquake excitation. *Earthquake Spectra*, *18*(4), 601-613.

[5] Shie, R. F., Ting, K., Yu, J. S., & Liu, C. T. (2007): The sliding and overturning analysis of a free-standing cask under earthquake. In *Solid State Phenomena*, 120, 207-212.

[6] Zhou, Q., & Yan, W. M. (2011): Sliding response of free-standing cultural relics under earthquakes by simulation. In *Advanced Materials Research*, 163, 2142-2146.

[7] Gazetas, G., Garini, E., Anastasopoulos, I., & Georgarakos, T. (2009): Effects of near-fault ground shaking on sliding systems. *Journal of geotechnical and geoenvironmental engineering*, *135*(12), 1906-1921.

[8] Nikfar, F., & Konstantinidis, D. (2016): Effect of the stick-slip phenomenon on the sliding response of objects subjected to pulse excitation. *Journal of Engineering Mechanics*, *143*(4), 04016122.

[9] Iwasaki, A., Nekomoto, Y., Morita, H., Taniguchi, K., Okuno, D., Matsuoka, T., & Chigusa, N. (2012): Experimental study on free standing rack loading full fuel assembly. In *ASME 2012 Pressure Vessels and Piping Conference*, 251-259.

[10] Younis, C. J., & Tadjbakhsh, I. G. (1984): Response of sliding rigid structure to base excitation. *Journal of engineering mechanics*, *110*(3), 417-432.

[11] Okada, T., & Takanashi, K. (1992): The resonance responses of steel structure with sliding floor loads. In *Proc. 10th World Conf. on Earthquake Engineering, Madrid*, 3, 4419-22.

[12] Chandrasekaran, A. R., & Saini, S. S. (1969): Live load effect on dynamic response of structures. *Journal of the Structural Division*.

[13] Ardila-Giraldo, O., Reyes, J. C., & Smith-Pardo, J. P. (2013): Contact interface modeling in the dynamic response of rigid blocks subjected to base excitation. In *4th ECCOMAS Them. Conf. on COMPDYN*.

[14] Smith-Pardo, J. P., Reyes, J. C., Ardila-Bothia, L., Villamizar-Gonzalez, J. N., & Ardila-Giraldo, O. A. (2015): Effect of live load on the seismic design of single-story storage structures under unidirectional horizontal ground motions. *Engineering Structures*, *93*, 50-60.

[15] Reyes, J. C., Ardila-Bothia, L., Smith-Pardo, J. P., Villamizar-Gonzalez, J. N., & Ardila-Giraldo, O. A. (2016): Evaluation of the effect of containers on the seismic response of pile-supported storage structures. *Engineering Structures*, *122*, 267-278.

[16] Reyes, J. C., Marcillo-Delgado, E., Smith-Pardo, J. P., & Ardila-Giraldo, O. A. (2018): Assessment of the Effective Seismic Mass for Low-Rise Framed Shear Buildings Supporting Nearly Permanent Live Loads. *Journal of Structural Engineering*, *144*(8), 04018098.

[17] IS 1893: 2016. (2016): Criteria for earthquake resistant design of structures.

[18] PEER (Pacific Earthquake Engineering Research Center). (2014): PEER ground motion database.

[19] American Society of Civil Engineers (ASCE). (2016): Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE/SEI 7-16.

