EFFECT OF LIVE LOAD OBJECTS ON THE RESPONSE OF PLATFORMS SUBJECTED TO UNIDIRECTIONAL GROUND MOTIONS

Juan C. REYES
Associate Professor, Universidad de los Andes, Colombia
jureyes@uniandes.edu.co

Luis ARDILA-BOTHIA
Research Assistant, University of Toronto, Canada
l.ardila@mail.utoronto.ca

J. Paul SMITH-PARDO
Assistant Professor, Seattle University, USA
smithjh@seattleu.edu

J. Nicolas VILLAMIZAR-GONZALEZ
Research Assistant, Universidad de los Andes, Colombia
jn.villamizar1341@uniandes.edu.co

Oscar A. ARDILA-GIRALDO
Ingetec, Colombia
oscarardila@ingetec.com.co

ABSTRACT: Although it is widely accepted that the seismic response of storage structures can be affected by the objects that they support, there are no consistent provisions in codes and standards regarding the treatment of live loads under earthquakes. An experimental program was conducted using a 1:15-scale model supporting a stiff block with the possibility to slide and/or rock in order to investigate the dynamic effect of live load objects on the seismic response of one-story storage structures. A total of 154 shake table tests were performed corresponding to permutations of five block-to-structure mass ratios, two block aspect ratios, and fourteen ground motion records which characterized service and contingency seismic hazard levels. Analyses of the experimental results showed that: 1) Drift demands on the one-story model were higher when the structure supported a squat block as compared to a slender block with the same mass; 2) a larger portion of the block's mass was effective as inertia for squat (sliding) blocks as compared to slender (rocking) blocks of the same mass; 3) the percentages of live load as inertia that are given in current design documents can be overly unconservative, especially for service-level ground motions and/or for squat live load objects.

1. Introduction

Design standard ASCE/SEI 7(2010) lists load cases that include the design earthquake combined with the full design live load; however, the standard also specifies that for storage structures only 25% of the design live load should be considered as seismic mass. For other types of structures and in other design documents, that percentage is smaller (POLB 2012) and even equal to zero (AASHTO 2012). This could suggest that from the live loads that can be expected to be present during an earthquake only a small portion effectively contributes to inertia on the structure. The provisions not only lack physical support but also they could be potentially unconservative when live load objects may not experience enough acceleration to slide or rock and thus behave as if they were rigidly attached to the structure. Only when the supporting floor acceleration is sufficient to cause relative movement of the objects, a portion of the live load effectively contributes to the inertial forces on the structure as energy is dissipated through friction (sliding) and/or impact (rocking/tipping). Therefore, contrary to the fixed percentages prescribed in design codes and standards, the extent to which live load contributes to inertial forces on the structure should depend on the intensity of the ground motion, the dynamic properties of the supporting structure, and the geometry and attachment conditions of the objects to the supporting floor.

Although significant amount of numerical and experimental research has been carried out on the dynamic response of rigid bodies under base excitation (Housner, 1963; Ishiyama, 1982; Pompei and Sumbatyan, 1998; Shenton, 1996; Sideris and Filiatrault, 2014) few have investigated the dynamic behavior of the structures supporting the rigid blocks themselves. Among those, Kounadis (2013) investigated the response of free-standing statues on the top surface of elastic cantilevers subjected to horizontal ground motion and developed criteria for the minimum ground acceleration that causes instability. Younis and Tadjbakhsh (1984), on the other hand, studied the dynamic behavior of a linear spring and a dashpot supporting a rigid rectangular body with the possibility to slide. They found that slippage increased when the mass of the structure was small relative to that of the block and that after a certain ground threshold frequency the absolute displacement of the rigid block became independent of the friction coefficient. Chandrasekaran and Saini (1969) used numerical integration to solve the equations of motion of an elastic single-degree-of-freedom system supporting a rigid block. The study considered alternative types of attachment of the rigid block such as elastic spring and viscous dashpot, Coulomb friction and dashpot, and rigidly mounted. The authors reported the ratio of the structure's drift when the block has a flexible connection to the structure's drift when the block is rigidly attached as a measure of the effect of live load on the seismic response of the structure. The analyses were conducted only for two particular ground motion records, and therefore the results lack statistical significance. More recently the authors (Smith-Pardo et. al, 2015) presented a lumped-parameter model that describes the seismic behavior of a SDF structure supporting a rigid block with the possibility to slide. A design expression was derived which allows estimating the portion of the live load that is effective as inertia in the seismic design of one-story storage structures. This investigation was supplemented by means of an experimental evaluation of the effect of live load -represented by a block—on the seismic response of a one-story platform structure (Reyes et. al, 2015).

2. Ground Motions

Two hazard levels were selected in this study in correspondence to those typically defined in specialized seismic design guidelines for piers and wharves (POLB 2012). The first is known as Operational Level Earthquake (OLE) and represents an event with a probability of 50% of being exceeded in 50 years. The second is defined as Contingency Level Earthquake (CLE) and corresponds to an event with a 10% probability of being exceeded in 50 years. For each hazard level, seven records with the characteristics listed in Table 1 were used in this study.

The ground motions, which corresponded to six shallow crustal earthquakes, were taken from the recommendations given by Earth Mechanics (2006) in a seismic vulnerability study for the port of Long Beach, California. Although both fault-normal (FN) and fault-parallel (FP) components of these records were modified to match the uniform hazard spectrum (UHS) for the site, only the FN component was used in this study. Scaling of the records was performed according to the ASCE/SEI 7-10 procedure using a method proposed by Reyes and Chopra (2012). Fig. 1 shows the 5%-damping scaled response spectrum for each record of the OLE and CLE events corresponding to an oscillator with a fundamental period of T=1.0 s

Table 1 - Selected records

	No.	Record name	Record station	M_w	*D* (km)
OLE	1	1989 Loma Prieta	Saratoga-aloha Ave.	6.9	13.0
	2	1987 Superstition Hill	Wildlife Liquefaction Array	6.3	24.7
	3	1987 Whittier	Northridge-Saticoy St.	6.0	39.8
	4	1979 Imperial Valley	EC CO Center FF	6.5	7.6
	5	1979 Imperial Valley	Calexico Fire Station	6.5	10.6
	6	1992 Erzikan	Erzikan	6.9	2.0
	7	1994 Northridge	Century City, LACC	6.7	25.7
CLE	1	1999 Hector Mine	Hector	7.1	12.0
	2	1989 Loma Prieta	Gilroy 03	6.9	13.0
	3	1979 Imperial Valley	Brawley	6.5	10.0
	4	1999 Duzce	Lamont 1059	7.1	4.0
	5	1992 Erzikan	Erzikan	6.7	4.0
	6	1940 Imperial Valley	El Centro	7.0	6.0
	7	1995 Kobe	Kobe University	6.9	1.0

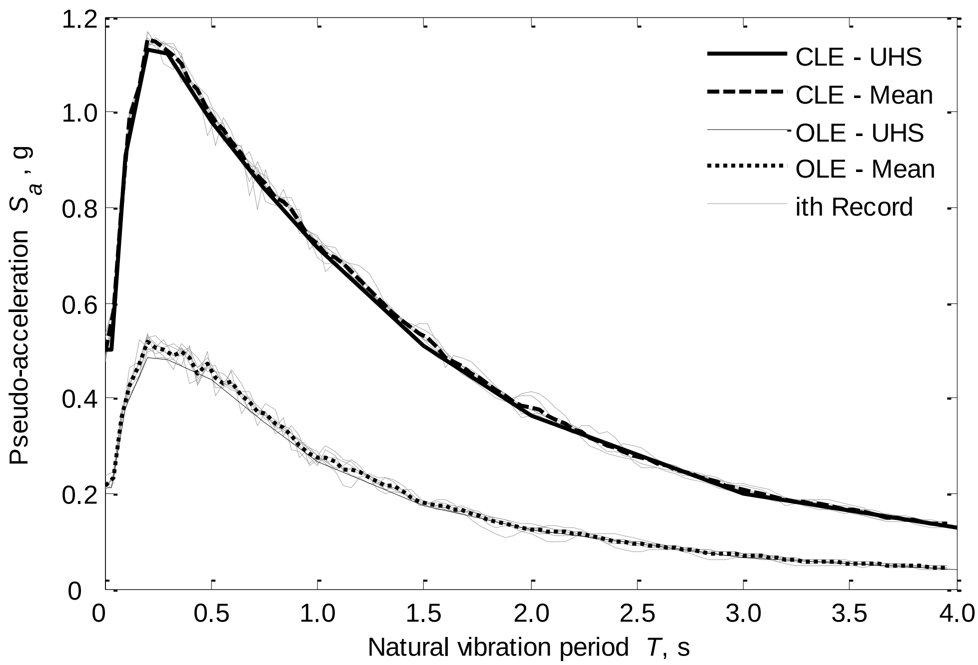


Fig. 1 – Uniform Hazard and Mean Acceleration Spectra for 5% Damping

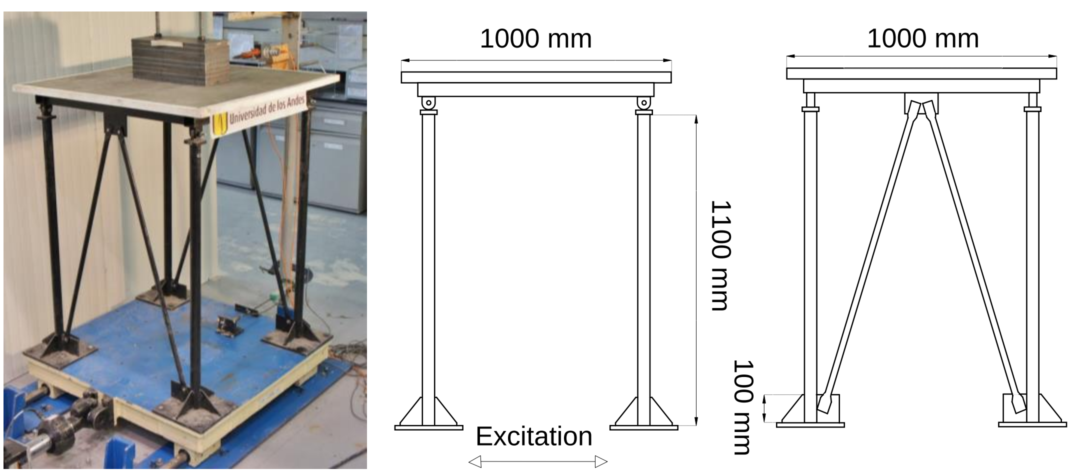
3. Experimental Program

The test model, shown in Fig. 2, represents an idealized portion of a floor on piles or columns at 7.5 meters on-center and supporting a rigid block with the possibility to slide or rock under base excitation.

Model columns were bolted to the shake table and consist of 1100-mm long steel tubes with 42-mm outer diameter by 2.5-mm wall thickness. The superstructure comprised a 1000 mm × 1000 mm deck supported by 50 mm × 50 mm × 3 mm-thick tubular steel beams. The deck was made up of a 12.5 mm-thick square plywood board with 25 mm × 15 mm wood planks along the edges, and a 15-mm layer of high strength mortar poured on top. Two inverted-V braces, each made of 20.5 mm-diameter by 1.5 mm-thick steel tubes, were used to limit motion of the specimen perpendicular to the direction of the excitation (Fig. 2c).

The lateral stiffness of the model structure had a median value of 59.3 kN/m and was obtained by applying a horizontal force to the platform through a hydraulic actuator and measuring the corresponding deflection with a draw-wire displacement transducer. The median values of the period and damping ratio from ten free vibration tests on the model structure alone (Fig. 2b) were $T_n = 0.21s$ and $\xi = 1.40\%$.The equivalent lumped mass of an equivalent single-degree-of-freedom (SDF) structure is $m_p =$ 66.3 kg, which, as expected, is higher than the measured superstructure mass of 63 kg.

A unidirectional shake table was used to apply the 14 ground motion records corresponding to OLE and CLE hazard levels. Accelerations were measured using one-directional accelerometers with a capacity range of 100 µg to 5 g, where g is the acceleration of gravity. Horizontal displacements were measured using linear variation differential transformers (LVDTs) with dynamic displacement precision of 0.01 mm and capacity of 100 mm. Displacement demands throughout the experimental program were at least three times below the estimated displacement corresponding to first yielding of the columns.



(a) (b) (c)

Fig. 2 – Experimental model: (a) overall view, (b) front and (c) side view with no block

The blocks used to represent live load objects consisted of a stack of 26 wood and steel plates with plan dimensions of 410 mm × 160 mm and a thickness of 19.2-mm. Alternative number of plates of each material were used as indicated in Table 2 to produce five different block-to-structure mass ratios $\alpha = m_b / m_p$ for the same block height H = 500 mm. The bottom plate was made of steel to represent concrete-to-steel contact interfaces (typical for container terminals). Static and kinematic Coulomb friction coefficients at the block-platform interface, μ_s and μ_k, were determined by slowly pulling the base of the block with a nylon string and measuring the peak force and the force associated to steady sliding of the block. For a total of 10 tests with blocks of different weights, median values of the friction coefficients were 0.42 and 0.31 respectively.

Table 2 - Characteristics of the Blocks Representing Live Load

Block	Number of wood plates	Number of steel plates	Block mass m_b , kg	Block-platform mass ratio $\alpha = m_b / m_p$
A	21	5	67.5	1.02
B	19	7	85.4	1.29
C	17	9	103.1	1.56
D	15	11	121.0	1.83
E	13	13	140.5	2.12

* $m_p =$ 66.3 kg (calculated based on the median of the measured period and the median of the measured lateral stiffness).

As shown in Fig. 3, two alternative block orientations were considered in the experimental program to study the effect of sliding versus rocking. When the long plan dimension was parallel to the direction of excitation the aspect ratio is $B/H =$ 410 mm/500 mm = 0.82 and the block tends to slide. When the short plan dimension was oriented parallel to the direction of the excitation the aspect ratio is $B/H =$ 160/500 = 0.32 and the block tends to rock. The two block width-to-height aspect ratios B/H permitted to evaluate the effect of friction versus block impact on the seismic response of the structure.

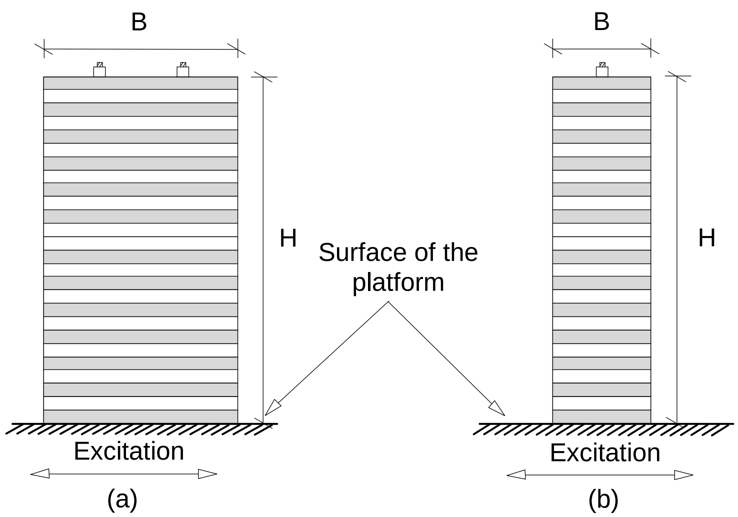
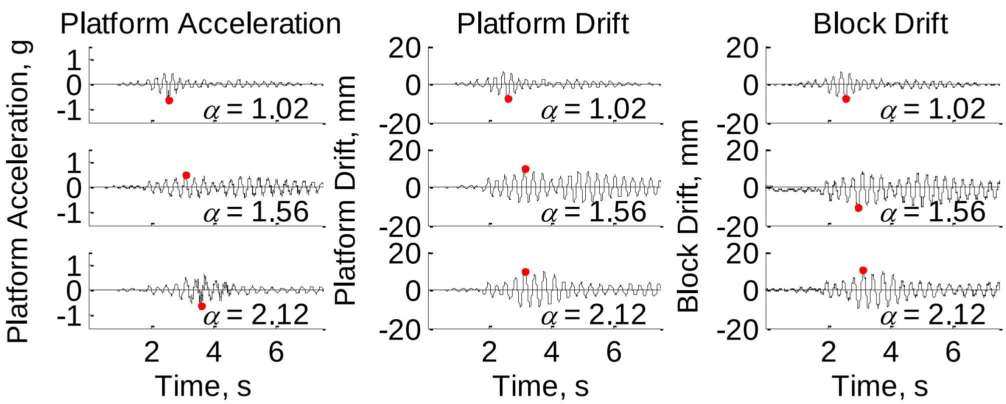


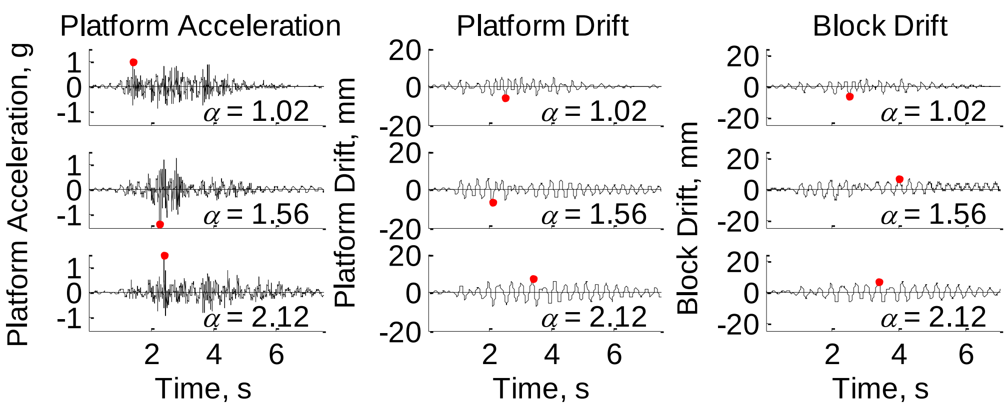
Fig. 3 – Block Aspect Ratio Relative to Direction of Excitation: a) Squat (B/H = 0.82) and b) Slender (B/H = 0.32)

A total of 154 shake table tests were performed in correspondence to a combination of five block-to-structure mass ratios α , two block aspect ratios B/H , seven service-level ground motions (OLE), and seven contingency-level ground motions (CLE). Examples of measured time history responses are shown in Fig. 4 for an OLE record and in Fig. 5 for a CLE record. Results for the other block-to-structure mass ratios α and for the remaining 12 records included in the experimental program can be found in Ardila-Bothia (2014). As evidenced by Fig. 5, CLE records produce significant relative movement of the block so energy dissipation through impact and friction can be significant. OLE records, however, produced small relative movement of the blocks and possibly insignificant energy dissipation.

Fig. 6 shows box plots of the measured maximum drifts of the model as a function of the block-to-structure mass ratio (α) for the two hazard levels and the two block aspect ratios (B/H). The open boxes represent median values for the model under the seven (OLE or CLE) ground motions, whereas tick marks correspond to the first and third quartiles. It is observed that drift demand is larger when the model structure supports a squat block versus a slender block of the same mass. This indicates that energy dissipation through sliding (friction) is smaller than energy dissipation through rocking (impact) of live load objects.



(a)



(b)

Fig. 4 – Experimental results of model structure under OLE record No. 7 when supporting: a) squat block (B/H = 0.82) and b) slender block (B/H = 0.32)

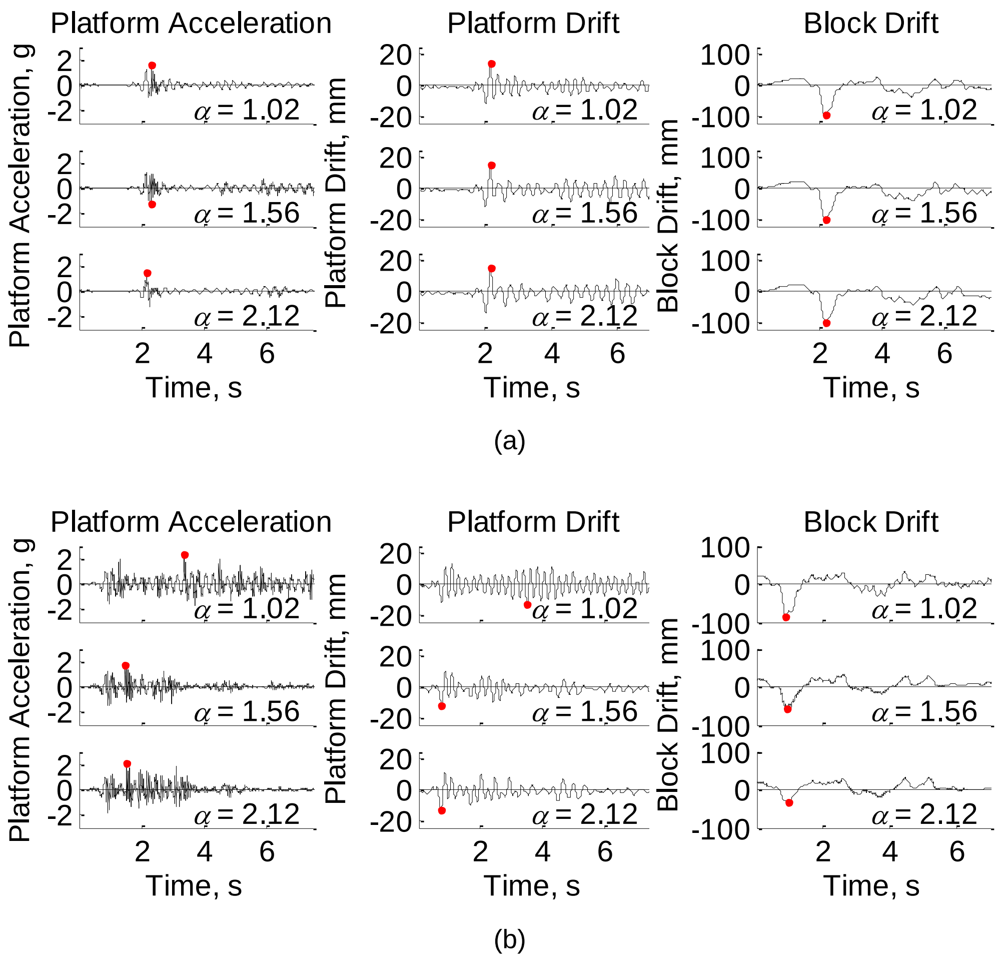


Fig. 5 – Experimental results of model structure under CLE record No. 3 when supporting: a) squat block (B/H = 0.82) and b) slender block (B/H = 0.32)

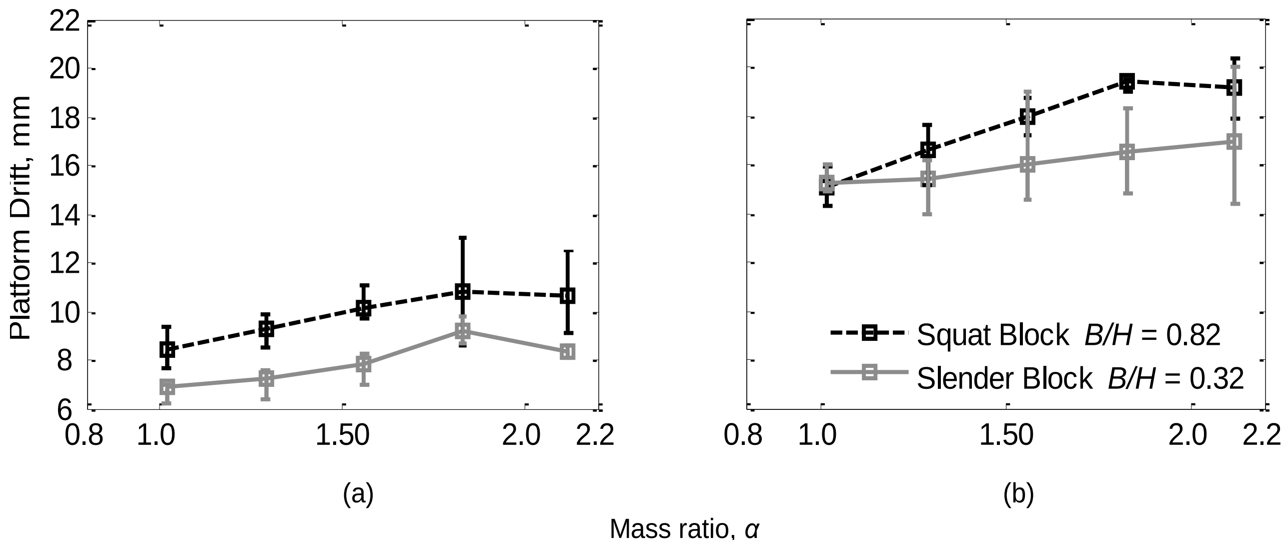


Fig. 6 – Maximum platform drift for: (a) Operational Level Earthquakes (OLE) and (b) Contingency Level Earthquakes (CLE)

4. Effective Portion of the Live Load as Inertia

In order to quantify the inertial effects associated to the relative movement of the block, a statistical approach was implemented in conjunction with the results from the experimental program. Consider an idealized version of the test specimen which consists of a SDF model supporting a block with the possibility to slide and/or rock (Fig. 7a). Consider also an equivalent SDF linear-elastic structure that supports no block as shown in Fig. 7b. The two structures have the same lateral stiffness k and viscous damping c, but the equivalent structure has a mass that is $(1+\alpha\lambda)$ times the mass of the actual test specimen with no block; where $\alpha = m_b / m_p$ is the block-to-structure mass ratio, and λ is a coefficient between zero and one that represents the portion of the block's mass that is effective as inertia. For a given set of seven OLE or seven CLE ground motions, λ is the value for which the mean of the maximum measured drift demands for the actual model structure with block $\bar{u}_p$ (Fig. 7a) is equal to the mean of the maximum calculated drift demands for the equivalent SDF system $\bar{u}_p^*$ (Fig. 7b). λ can be found using the following iterative algorithm for a given block-to-structure mass ratio α and block slenderness ratio B/H:

1. Select trial values of the portion of live load as inertia between zero and one; λ_i = 0, …1.0.
2. For each value of λ_i, calculate a trial period and damping ratio $T_{\lambda i} = T\sqrt{1+\alpha\lambda_i}$ and $\xi_{\lambda i} = \xi / \sqrt{1+\alpha\lambda_i}$; where $T = 0.21s$ and $\xi = 1.40\%$. Calculate also the mean of the maximum platform drifts $(\bar{u}_p^*)_i$ of the trial equivalent structure under the seven scaled shake table ground acceleration records (OLE or CLE).
3. Calculate the mean of the measured maximum platform drifts $\bar{u}_p$ of the actual model structure with block under the seven scaled ground motion records.
4. Plot $(\bar{u}_p^*)_i$ versus the trial portions of the live load as inertia and estimate the value of $\lambda = \lambda_i$ for which $(\bar{u}_p^*)_i = \bar{u}_p$

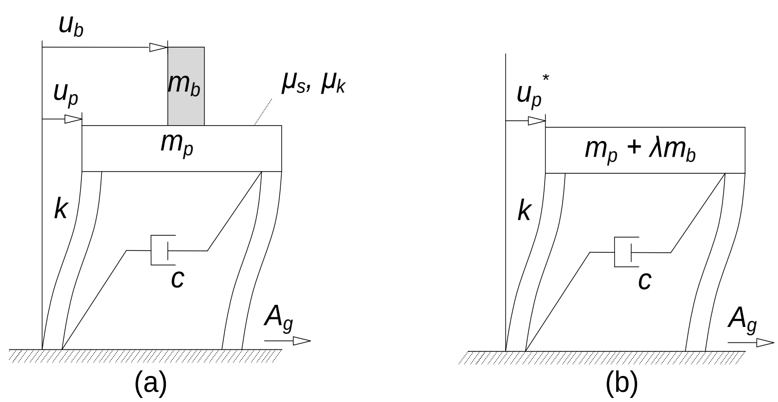


Fig. 7 – Equivalency to determine the portion of the block's mass (λ) that is effective as inertia: a) SDF idealization of actual test specimen, and b) equivalent SDF system

Fig. 8 shows the estimated values of λ as a function of the mass ratio α, using the algorithm previously presented and test results. It can be appreciated that the portion of the block's mass that is effective as inertia is influenced by the level of seismic excitation, and the block's aspect ratio (B/H). For example, for service-level ground motions (OLE), λ ranges between 0.5-0.8 for slender blocks ($B/H = 0.32$), and is equal to or higher than 0.9 for squat blocks ($B/H = 0.82$).

For service-level ground motions, the inertial forces developed in the supporting structure are insufficient to induce significant sliding or rocking of the block. Therefore, values of λ were higher than 0.5 for all cases. For contingency level earthquakes (CLE), λ reduces to nearly 0.2 for slender blocks and to 0.2-0.5 for squat blocks, as more energy is dissipated through impact/rocking of the block. Notice that the values of λ for squat blocks are consistent with the larger drifts that were measured in the tests for B/H = 0.82 (Fig. 6).

For pile-supported container terminals, in which the interface between live load (containers) and platform is steel-on-concrete, Fig. 8 implies that the percentages of live load as inertia suggested in current design documents (10%) can be overly unconservative, especially for service-level ground motions and squat live load objects.

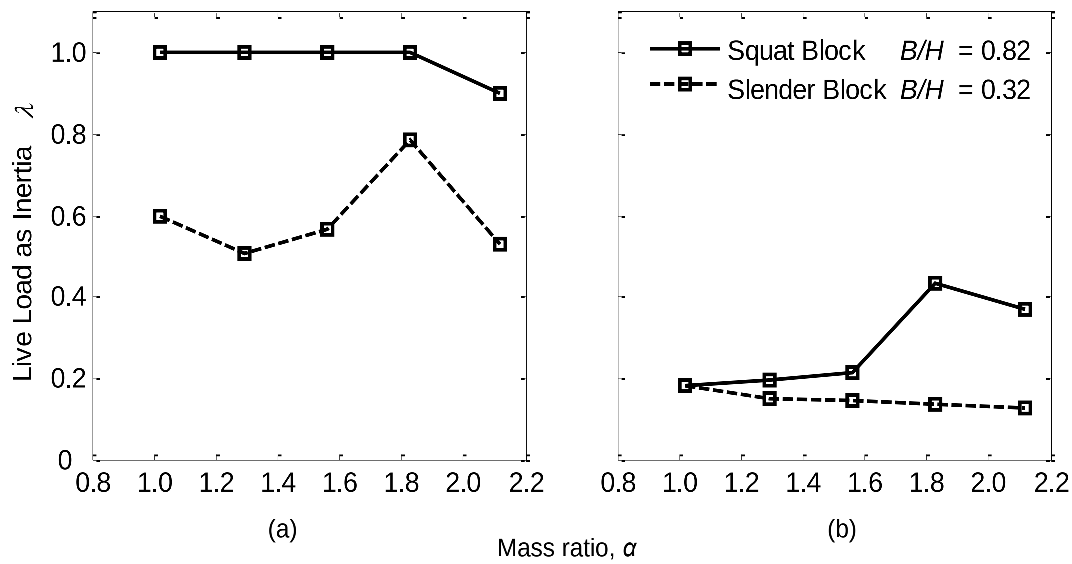


Fig. 8 – Experimentally-obtained portion of live load as inertia (λ) for: (a) Operational Level Earthquakes (OLE) and (b) Contingency Level Earthquakes (CLE)

5. Summary and Conclusions

With the goal to assess the dynamic effect of live load on the seismic response of storage structures, 154 shake table tests were performed using a 1:15 scale single-story model supporting a block with the possibility to slide and/or rock. The experimental program considered five block-to-structure mass ratios α, two block aspect ratios B/H, seven service-level earthquakes (OLE), and seven contingency level earthquakes (CLE). The main findings from this study are:

- Drifts measured from tests with the single-story model supporting a squat block were higher, as compare to those with a slender block with the same mass. This implies that the energy dissipated through rocking/impact is higher, when compared with sliding alone. Consistent with this, a larger portion of the block's mass was found to be effective as inertia for the squat blocks, as compared to slender blocks with the same mass.
- For service-level earthquakes, the portion of the block´s mass effective as inertia was found to be between 50% and 80% for slender blocks, and between 90% and 100% for squat blocks. Thus, for this level of seismic hazard, the percentages of live load as inertia provided in current design codes can be overly unconservative.
- For contingency level earthquakes, the portion of the block´s mass that was effective as inertia was nearly 20% for slender blocks and between 20% and 50% for squat blocks.

6. References

American Association of State Highway Transportation Officials, "AASHTO LRFD Bridge design specifications and commentary". 6th Edition. 2012

ARDILA-BOTHIA, Luis, "Efecto de la carga viva en el diseño sísmico de estructuras de almacenamiento de un piso", MS Thesis (in Spanish), Departamento de Ingeniería Civil y Ambiental. Universidad de los Andes, Bogotá, Colombia. 2014.

ASCE/SEI 7-10, "Minimum design loads for buildings and other structures", American Society of Civil Engineering, 2010.

CHANDRASEKARA, AR, SAIN, SS, "Live load effect on dynamic response of structures", *Journal of Structural Engineering Division*, Vol 5, ST4, 1969, pp. 649-659.

EARTH MECHANICS, "Port-wide ground motion study port of Long Beach", Final report, 2006.

HOUSNER, GW, "The behavior of inverted pendulum structures during earthquakes", *Bulletin of the Seismological Society of America*, Vol. 53, No. 2, 1963, pp. 403-417.

ISHIYAMA, Y, "Motions of rigid bodies and criteria for overturning by earthquake excitations", *Earthquake Engineering & Structural Dynamics*. Vol. 10, No. 5, 1982, pp. 635–650.

KOUNADIS, A, "Rocking instability of free-standing statues atop slender cantilevers under ground motion", *Soil Dynamics & Earthquake Engineering*, Vol. 48, pp. 294-305.

Port of Long Beach (POLB), "Wharf design criteria", Version 3.0, 2012.

POMPEI, A, SCALIA, A, SUMBATYAN, MA, "Dynamics of rigid block due to horizontal ground motion", *Journal of Engineering Mechanics*. Vol. 124, no. 7, 1998, pp. 713–717.

REYES, JC, CHOPRA, AK, "Modal pushover-based scaling of two components of ground motion records for nonlinear RHA of buildings", *Earthquake Spectra*. Vol. 28, No. 3, pp.1243-1267.

REYES, JC, ARDILA-BOTHIA, L, SMITH-PARDO, JP, VILLAMIZAR-GONZALEZ JN, ARDILA-GIRALDO OA, "Experimental evaluation of the effect of live load on the seismic response of single-story structures under unidirectional ground motions", *Engineering Structures*, 2015, Under review.

SHENTON, HW, "Criteria for initiation of slide, rock, and slide-rock rigid-body modes", Journal of Engineering Mechanics, Vol. 122, No. 7, 1996, pp. 690-693.

SIDERIS, P, FILIATRAULT, A, "Seismic response of squat rigid bodies on inclined planes with rigid boundaries", Journal of Engineering Mechanics. Vol. 140, No. 1, 2014, pp. 149-158.

SMITH-PARDO, JP, REYES, JC, ARDILA-BOTHIA, L, VILLAMIZAR-GONZALEZ, JN, ARDILA-GIRALDO, OA, "Effect of live load on the seismic design of single-story storage structures under unidirectional horizontal ground motions", Engineering Structures. Vol. 93, 2015, pp. 50-60.

YOUNIS, CJ. TADJBAKHSH, IG, "Response of sliding rigid structure to base excitation", Journal of Engineering Mechanics. Vol. 110, No. 3, pp. 417-432.