International Journal of Civil Engineering

Structure
Earthquake

The effect of foundation uplift on elastic response of soil-structure systems

A.H. Jafarieh[1], M.A. Ghannad[2,]*
Received: November 2012, Revised: July 2013, Accepted: November 2013

Abstract

It is well-known that the behavior of soil-structure systems can be well described using a limited number of non-dimensional parameters. This is the outcome of researches based on the premise that the foundation is bonded to the ground. Here, it is shown the concept can be extended to systems with foundation uplift. A set of non-dimensional parameters are introduced which controls the main features of uplifting systems. The effect of foundation uplift on response of soil-structure systems are investigated parametrically through time history analysis for a wide range of systems subjected to ground motions recorded on different soil types. In particular, the effects of uplift on displacement ratio, defined as the ratio of maximum displacement of the uplifting system to that of the elastic system without uplifting and drift ratio, defined as the ratio of maximum drift of the structure as a part of uplifting soil-structure system to that of the elastic system without uplifting, are investigated. It is observed that in general foundation uplift reduces the drift response of structures, which in turn, results in lower base shear. The reduction reaches about 35 percent for slender structures located on relatively soft soils subjected to strong ground motions. Simplified expressions are suggested to estimate this reduction in the base shear.

Keywords: *Soil-structure interaction, Foundation uplift, Displacement ratio, Drift ratio.*

1. Introduction

It is more than three decades that the effect of soil on seismic performance of structures has been known for engineers. It is well known that response of a structure supported on soil may be different from that of the identical structure in the fixed-base state, due to soil-structure interaction (SSI). The principal effect of the interaction is to increase the natural period of the structure and, usually, to increase its effective damping ratio [1, 2, 3]. Thus, it was suggested to replace the soil-structure system by an equivalent SDOF system with modified period and modified damping ratio. This idea has formed the basis of SSI related regulations in current seismic provisions.

In most of researches done on interaction of soil and structures with shallow foundation it is assumed the foundation is bonded to the ground. However, several examples of structures that experienced uplifting from the supporting soil have been reported during real earthquakes such as Chile 1960, Alaska 1964, San Fernando 1971, Kocalie 1999, and Athens 1999 [4]. Uplifting can make changes in force-displacement behavior of soil structure systems. These changes may lead to increase or decrease in structural demands. As uplifting occurs the length of contact between soil and foundation reduces, which changes the dynamic stiffness of soil contribution to the soil-structure system. Therefore, any rational study on response of soil-structure systems should consider the effect of possible foundation uplift. Several researchers have studied the response of uplifting systems. These investigations can be classified into two main categories.

The first group focused on the rocking responses of rigid blocks on rigid or flexible base. Housner [5] used an energy based approach to study the role of excitation frequency in the overturning potential of the systems. The outcome of his research later formed the basis of FEMA-356 [6] guideline for checking the overturning potential of structures. Psycharis and Jennings [7] also studied the subject by using Winkler type visco-elastic springs to model the soil beneath the foundation. Makris and Konstantindis [8] showed the traditional response spectrum method should not be used for studying performance of rocking systems. They also suggested using the so-called rocking spectrum instead. Gazetas and Apostolou [9] studied the simultaneous effects of foundation uplift and soil yielding and concluded under certain conditions uplifting can be quite beneficial for the superstructure. Apostolou *et al.* [4] studied uplifting of slender rigid blocks under harmonic excitation to find the relation between overturning acceleration and excitation frequency. The subject was also studied by Ishiyama [10] and Yim, *et al.* [11], among the others, to establish criteria

** Corresponding author: ghannad@sharif.edu*
1 PhD Candidate, Sharif University of Technology, Tehran, Iran
2 Associate Professor, Sharif University of Technology, Tehran, Iran

for overturning, by earthquake excitations.

The second group paid attention to response of flexible structures. Meek [12] analyzed a flexible single degree of freedom system resting on soil and pointed to the reduction in base shear of structure due to uplift. He concluded that the reduction will be more for more slender structures. Yim and Chopra [13] used a single degree of freedom model for the structure resting on distributed Winkler springs and came to the same conclusion, especially for short period structures. Then, Chopra and Yim [14] presented simplified equations to predict the induced base shear for systems allowed to uplift. Oliveto *et al.* [15] studied the uplift phenomenon under impulsive and earthquake excitations by considering large deformations. More recently, Khoshnoudian *et al.* [16] used the finite element method to investigate the effects of foundation uplift on the response of soil-structure systems considering nonlinear material behavior. Acikgoz and Dejong [17] also compared the fundamental dynamic properties of flexible rocking structures with those of similar linear elastic systems and rigid rocking structures. It was revealed that flexible configurations are more resistant to toppling but they may experience excessive deformation because of uplift resonance.

Most of the above mentioned studies are devoted to case studies or simplified models which cover limited practical cases. Moreover, the radiation damping due to SSI has not been properly addressed. In this study the response of uplifting soil-structure systems is studied parametrically for a wide range of parameters which covers most practical structures. A number of non-dimensional key parameters are introduced, which control the main features of uplifting systems. This provides a better understanding of the phenomenon. The soil induced damping is modeled more realistically such that the response of systems with no uplift converges to the expected response of the corresponding soil-structure systems. The effect of the introduced key parameters on seismic demands of the structure is studied and simplified expressions are suggested to estimate the change in the base shear response of the structure due to uplift.

2. Soil-Structure Model

Figure 1 shows a simplified model used to represent the soil-structure system. The structure is considered as an elastic single degree of freedom system with the same period, T_{str}, and damping ratio, ζ_{str}, as in the first mode of vibration of the fixed-base structure. The lumped mass, m_{str}, and the height, h, are the effective mass and the effective height of the structure, respectively. The foundation is assumed to be rigid and the soil beneath the foundation is replaced by set of spring-damper elements with frequency independent coefficients. The coefficients of horizontal spring and damper, attached to the center of foundation, are as follows:

$$k_x = \frac{8}{2-\upsilon} G r_x \tag{1}$$

$$c_x = \frac{\pi}{8}(2-\upsilon)\frac{r_x}{V_S} k_x \tag{2}$$

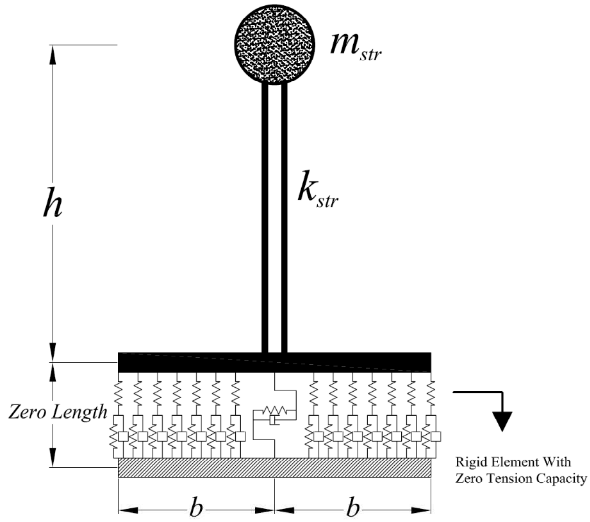


Fig. 1 Soil-structure model

in which G, V_S and υ are the shear modulus, shear wave velocity and Poisson's ratio of soil, respectively. r_x is the radius of the equivalent circular foundation for translation defined as $r_x = \sqrt{A_f / \pi}$ where A_f is the area of foundation's footprint. These coefficients are proposed by Wolf [18] for surface foundations.

Also, as shown in Fig. 1, distributed vertical springs and dampers are considered for modeling vertical and rotational stiffness of soil. A rigid tensionless spring is introduced in series with each pair of vertical spring-damper to allow foundation uplift. The coefficients of vertical distributed springs and dashpots and their spacing are determined in a way to produce proper stiffness and damping for rocking motion of surface foundations, k_θ and c_θ, as follows [18]:

$$k_\theta = \frac{8}{3(1-\upsilon)} G r_\theta^3 \tag{3}$$

$$c_\theta = \frac{3\pi}{16}(1-\upsilon)\frac{r_\theta}{V_S} k_\theta \tag{4}$$

in which r_θ is the radius of the equivalent circular foundation for the rotational degree-of-freedom defined as $r_\theta = \sqrt[4]{4I_f / \pi}$ where I_f is the foundation's moment of inertia about its diameter.

3. Key Parameters of Uplifting Soil-Structure Systems

It is a common practice to replace the soil-structure system with an equivalent fixed-base model with equivalent period, T_{ssi}, and equivalent damping ratio, ξ to approximate the system's response in the absence of foundation uplift [19, 20]. Moreover, there are well-established methods to calculate the equivalent parameters of the replacement system [1, 2, 21]. The equivalent damping ratio of the system is usually computed as a function of the period change and the aspect ratio of the structure, *h/b*, which is defined as the ratio of its height to the dimension of foundation [22]. Thus, the key parameters to evaluate the effect of SSI on elastic response of structures would be the ratio of the period of the soil-structure system to that of the fixed-base model, T_{ssi}/T_{str}, and the aspect ratio of the structure. This has been formed the basis of regulations on SSI since its inception in 1978 [23].

Now, consider the model of Fig. 1 for soil-structure systems in which foundation uplift is allowed to occur. Prior to any dynamic excitation at base, the system experiences vertical displacement S_f as follows due to gravity loads,

$$s_f = \frac{m_{str} g}{2bk_v} \tag{5}$$

where k_v is the vertical stiffness per unit length of foundation and g is the acceleration due to gravity. During vibration of the system the deformation of springs is not uniform and also varies with time. At any instant of time when one edge of the foundation reaches the natural unstressed state of the spring elements, uplift starts. After that, if the upward displacement of that edge continues, an increasing portion of the foundation mat will uplift from the supporting elements.

Figure 2 schematically shows the force-displacement behavior of the uplifting system. Since a linear elastic behavior is assumed for the soil and the structure, the only source of nonlinearity would be due to foundation uplift. When the applied horizontal load gradually increases, the settlement at one edge of the foundation will decrease until the first spring at that edge becomes unstressed. This is the condition of *incipient uplift* of foundation from the supporting elements. At this moment, the deformation at the opposite edge of the foundation will be $s_R = m_{str} g / k_v b$ which is twice s_f. The required horizontal load for the condition of incipient uplift, P_{iu}, and the corresponding total displacement of the system are calculated from rotational equilibrium of the system:

$$P_{iu} = \frac{m_{str} gb}{3h} \tag{6}$$

$$\Delta_{iu} = \frac{m_{str} gb}{3h}\left(\frac{1}{k_{str}} + \frac{1}{k_x} + \frac{h^2}{k_\theta}\right) \tag{7}$$

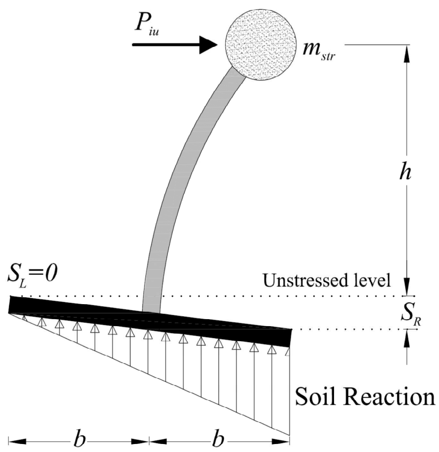
As shown in Fig. 2(b) there is an ultimate value for the horizontal force, P_{over}, after which overturning occurs.

$$P_{over} = \frac{m_{str} gb}{h} \tag{8}$$

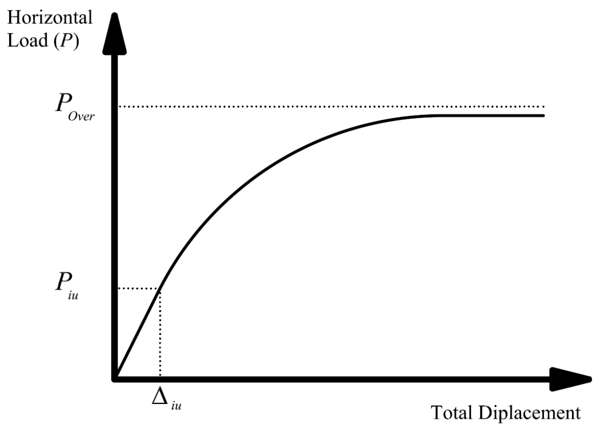
Here, a new parameter is introduced as *uplift index*, which is defined as the ratio of the elastic strength demand of the system not allowed to uplift, $(F_{el})_{NoUplift}$, to P_{iu}.

$$R_d = \frac{(F_{el})_{NoUplift}}{P_{iu}} \tag{9}$$

Therefore, the key parameters which define uplifting soil-structure systems are listed as T_{ssi}/T_{str}, h/b and R_d along with the period of the structure in the fixed-base state, T_{str}. It should be noted that there are some other parameters with less importance which can be set to some typical values [21, 22]. The mass ratio defined as $\gamma = m_{str} / \rho\pi r_\theta^2 h$, in which ρ is the mass density of soil, is one of these parameters which can be set to 0.15 for ordinary building type structures [24]. Poisson's ratio of soil is considered to be $\upsilon = 0.4$ and the material damping ratios for both the soil and the structure are set to 5% of the critical damping.



(a) Incipient of uplift



(b) Static force-displacement behavior of the system

Fig. 2 Static pushover analysis for elastic soil-structure systems allowed to uplift

4. Methodology

It is intended to study the effect of foundation uplift on elastic response of soil-structure systems parametrically. This is done by analyzing the soil-structure model of Fig. 1 for a wide range of non-dimensional parameters introduced in the previous section subjected to ground motions recorded on different soil types. The open-source software OpenSees (Open System for Earthquake Engineering Simulation) [25] of the Pacific Earthquake Engineering Research Center is used. A family of 540 soil-structure systems with periods T_{ssi}=0.1 to 3 seconds having three different values of aspect ratio, h/b=1, 2 and 5, as the representatives of short, medium-rise and tall buildings, and three values of period elongation ratio, T_{ssi}/T_{str}=1.1, 1.5 and 2, are investigated. Soil-structure systems with period elongation T_{ssi}/T_{str}=2 are systems with dominant SSI effect while those with T_{ssi}/T_{str}=1.1 are representatives of nearly fixed-base structures. All systems are analyzed subjected to 60 ground motions provided by FEMA-440 [24] for site classes B, C and D (Table 1).

Table 1 Selected ground motions' characteristics

(a) Ground Motions Recorded on Site Class B

Number	Date	Earthquake Name	Magnitude (Ms)	Station Name	Station Number	Component (deg)	PGA (cm/s)
1	6/28/92	Landers	7.5	Silent Valley, Poppet Flat	12206	0	48.9
2	6/28/92	Landers	7.5	Twntynine Palms Park Maintenance Bldg	22161	0	78.7
3	6/28/92	Landers	7.5	Amboy	21081	90	146
4	10/17/89	Loma Prieta	7.1	Point Bonita	68043	297	71.4
5	10/17/89	Loma Prieta	7.1	Piendmont, Piendmont Jr. High Grounds	58338	45	81.2
6	10/17/89	Loma Prieta	7.1	San Francisco, Pacific Height	58131	270	60.2
7	10/17/89	Loma Prieta	7.1	San Francisco, Rincon Hill	58151	90	88.5
8	10/17/89	Loma Prieta	7.1	San Francisco, Golden Gate Bridge	1678	360	228.6
9	10/17/89	Loma Prieta	7.1	Hollister-SAGO Vault	1032	360	60.1
10	10/17/89	Loma Prieta	7.1	South San Francisco, Sierra Point	58539	205	102.7
11	10/17/89	Loma Prieta	7.1	Berkeley, Lawrence Berkeley Lab.	58471	90	114.8
12	10/17/89	Loma Prieta	7.1	Coyote Lake Dam, Downstream	57504	285	175.6
13	1/17/94	Northridge	6.8	Mt Wilson, CIT Seismic Station	24399	90	228.5
14	1/17/94	Northridge	6.8	Antelope Buttes	24310	90	99.7
15	1/17/94	Northridge	6.8	Los Angeles, Wonderland	90017	185	168.7
16	1/17/94	Northridge	6.8	Wrightwood, Jackson Flat	23590	90	54.5
17	1/17/94	Northridge	6.8	Littlerock-Brainard Can	23595	90	7.2
18	1/17/94	Northridge	6.8	San Gabriel, E. Grand Ave.	90019	180	256
19	10/1/87	Whittier Narrows	6.1	Los Angeles, Gritfith Park Observatory	141	0	133.8
20	10/15/79	Imperial Valley	6.8	Superstition Mountain	286	135	189.2

(b) Ground Motions Recorded on Site Class C

Number	Date	Earthquake Name	Magnitude (Ms)	Station Name	Station Number	Component (deg)	PGA (cm/s2)
1	10/15/79	Imperial Valley	6.8	El Centro, Parachute Test Facility	5051	315	200.2
2	2/9/71	San Fernando	6.5	Pasadena, CIT Athenaeum	80053	90	107.9
3	2/9/71	San Fernando	6.5	Pearblossom Pump	269	21	133.4
4	6/28/92	Landers	7.5	Yermo, Fire Station	12149	0	167.8
5	10/17/89	Loma Prieta	7.1	APEEL 7, Pulgas	58378	0	153
6	10/17/89	Loma Prieta	7.1	Gilroy #6, San Ysidro Microwave site	57383	90	166.9
7	10/17/89	Loma Prieta	7.1	Saratoga, Aloha Ave.	58065	0	494.5
8	10/17/89	Loma Prieta	7.1	Gilroy, Gavilon College Phys Sch Bldg	47006	67	349.1
9	10/17/89	Loma Prieta	7.1	Santa Cruz, University of California	58135	360	433.1
10	10/17/89	Loma Prieta	7.1	San Francisco, Diamond Heights	58130	90	110.8
11	10/17/89	Loma Prieta	7.1	Fremont, Mission San Jose	57064	0	121.6
12	10/17/89	Loma Prieta	7.1	Monterey, City Hall	47377	0	71.6
13	10/17/89	Loma Prieta	7.1	Yerba Buena Island	58163	90	66.7
14	10/17/89	Loma Prieta	7.1	Anderson Dam, Downstream	1652	270	239.4
15	4/24/84	Morgan Hill	6.1	Gilroy, Gavilon College Phys Sci Bldg	47006	67	95
16	4/24/84	Morgan Hill	6.1	Gilroy #6, San Ysidro Microwave Site	57383	90	280.4
17	7/8/86	Palmsprings	6	Fun Valley	5069	45	129
18	1/17/94	Northridge	6.8	Littlerock, Brainard Canyon	23595	90	70.6
19	1/17/94	Northridge	6.8	Castaic, Old Ridge Route	24278	360	504.2
20	1/17/94	Northridge	6.8	Lake Hughes #1, Fire station #78	24271	0	84.9

(c) Ground Motions Recorded on Site Class D

Number	Date	Earthquake Name	Magnitude (Ms)	Station Name	Station Number	Component (deg)	PGA (cm/s2)
1	6/28/92	Landers	7.5	Yermo, Fire Station	22074	270	240
2	6/28/92	Landers	7.5	Palm Springs, Airport	12025	90	87.2
3	6/28/92	Landers	7.5	Pomona, 4th and Locust, Free Field	23525	0	65.5
4	1/17/94	Northridge	6.8	Los Angeles, Hollywood Storage Bldg.	24303	360	381.4
5	1/17/94	Northridge	6.8	Santa Monica City Hall	24538	90	866.2
6	1/17/94	Northridge	6.8	Los Angeles, N. Westmoreland	90021	0	393.3
7	10/17/89	Loma Prieta	7.1	Gilroy 2, Hwy 101 Bolsa Road Motel	47380	0	394.2
8	10/17/89	Loma Prieta	7.1	Gilroy 3, Sewage Treatment Plant	47381	0	531.7
9	10/17/89	Loma Prieta	7.1	Hayward, John Muir School	58393	0	166.5
10	10/17/89	Loma Prieta	7.1	Agnews, Agnews State Hospital	57066	0	163.1
11	10/1/87	Whittier Narrows	6.1	Los Angeles, 116th St School	14403	270	288.4
12	10/1/87	Whittier Narrows	6.1	Downey, County Maintenance Bldg	14368	180	193.2
13	10/15/79	Imperial Valley	6.8	El Centro #13, Strobel Residence	5059	230	136.2
14	10/15/79	Imperial Valley	6.8	Calexic, Fire Station	5053	225	269.6
15	4/24/84	Morgan Hill	6.1	Glroy #4, 2905 Anderson Rd	57382	360	341.4
16	4/24/84	Morgan Hill	6.1	Gilroy #7, Mantnilli Ranch, Jamison Rd	57425	0	183
17	4/24/84	Morgan Hill	6.1	Gilroy #2, Keystone Rd	47380	90	207.9
18	4/24/84	Morgan Hill	6.1	Gilroy #3 Sewage Treatment Plant	47381	90	189.8
19	2/9/71	San Fernando	6.5	Los Angeles, Hollywood Storage Bldg.	135	90	207
20	2/9/71	San Fernando	6.5	Vernon, Cmd Terminal Building 4814 Loma Vista	288	277	104.6

First, it is assumed the foundation is not allowed to uplift. The elastic shear strength demand, $(F_{el})_{NoUplift}$, is evaluated for each soil-structure system subjected to any given ground motion. Having P_{iu}, which is a characteristic of the system, and independent of the applied excitation, R_d is calculated using Eq. (9) for the given ground motion. Thus, different values for R_d can be resulted for any specific soil-structure system by simply scaling the PGA of the ground motion. Here, for each soil-structure system, ground motions are scaled in a way to provide five values for uplift index (R_d =1.5, 2, 2.5, 3 and 4). The scaled ground motions are then used to analyze soil-structure systems allowed to uplift. Accordingly, the *displacement ratio* is defined as follows.

$$C_d = \frac{(\Delta_{el})_{Uplift}}{(\Delta_{el})_{NoUplift}} \tag{10}$$

The numerator of the right-hand side of Eq. (10) is the resulting maximum displacements for the soil-structure systems when foundation uplift is allowed while the denominator is the result of analysis done in the first step for the corresponding uplift index. Also, in order to study the effect of foundation uplift on the performance of the super-structure, as a part of soil-structure system, a new parameter is defined in Eq. (11) as drift ratio.

$$C_{dr} = \frac{(Drift_{el})_{Uplift}}{(Drift_{el})_{NoUplift}} \tag{11}$$

The numerator and denominator of the right-hand side of Eq. (11) are the resulting maximum drift of the structure, as a part of soil-structure system, when foundation uplift is and is not allowed, respectively.

In this research, the displacement ratio defined in Eq. (10) and the drift ratio defined in Eq. (11) are computed for a wide range of non-dimensional parameters defined in the previous section. The average of results are then presented and discussed. For this purpose the mean of the resulting displacement and drift ratios are calculated for all ground motions while the records are scaled to provide the same uplift index, R_d.

5. Displacement Ratios

The effect of the introduced key parameters on displacement ratio, defined in Eq. (10), is studied in this section. For this purpose the response of a wide range of soil-structure systems subjected ground motions recorded on different soil types are studied. Figure 3 shows the smoothed curves for mean values of C_d for different soil-structure systems subjected to 20 ground motions recorded on site class C provided by FEMA 440 [24]. The ground motions are scaled to provide five values of uplift index ranging from 1.5 to 4. As expected, it can be seen that for all systems C_d increases by increasing R_d. In the other words the total displacement of the system increases as a result of more foundation uplift. That is because the period of the soil-structure system increases due to foundation uplift and, in the same time, the induced radiation damping in soil decreases due to smaller contact area between the foundation element and soil. The effect of R_d on C_d is more significant for systems with short periods, leading to very large values for R_d>3. It should be noted that R_d=3 is a large value which results in overturning of the system in static pushover analysis (see Fig. 2). In the dynamic analysis of the system, however, much larger values of R_d is required to cause overturning and none of systems studied in Fig. 3 experience overturning. This can be examined by using the criterion introduced in FEMA-356 [6] for overturning control.

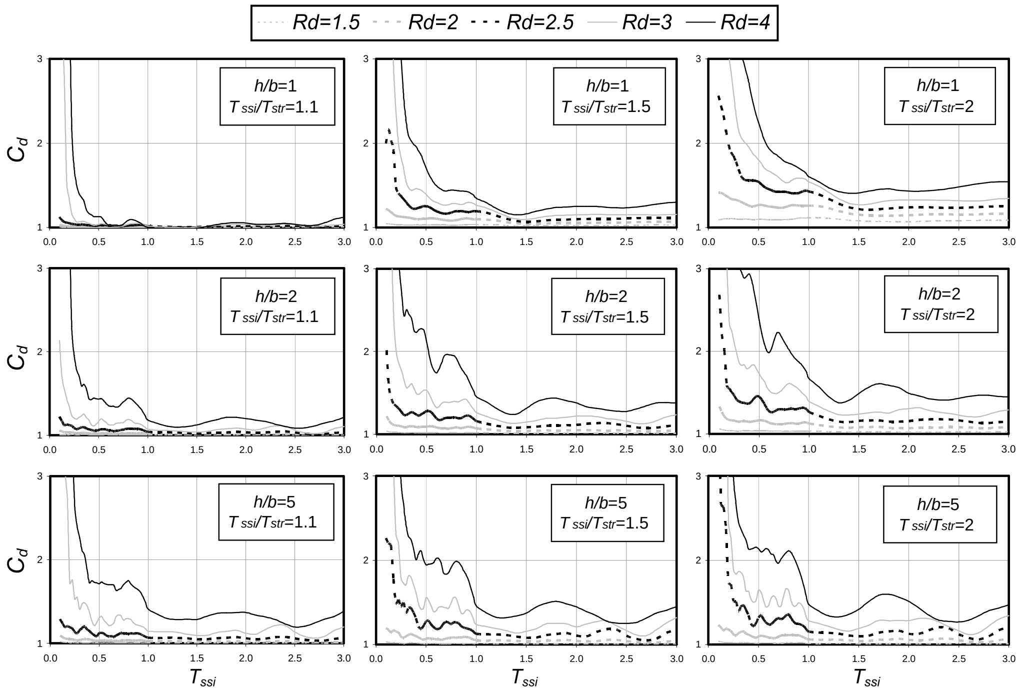
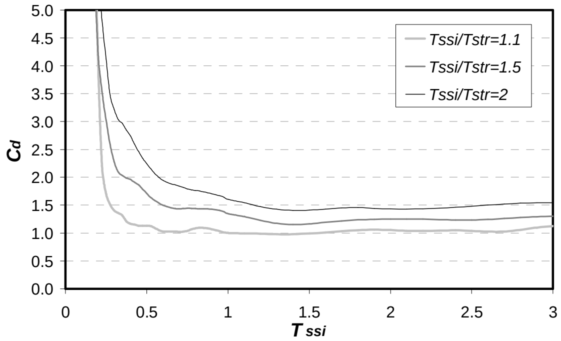
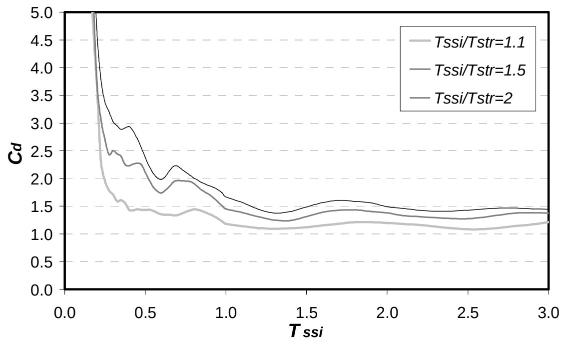


Fig. 3 C_d for different soil-structure systems subjected to the records of site class C

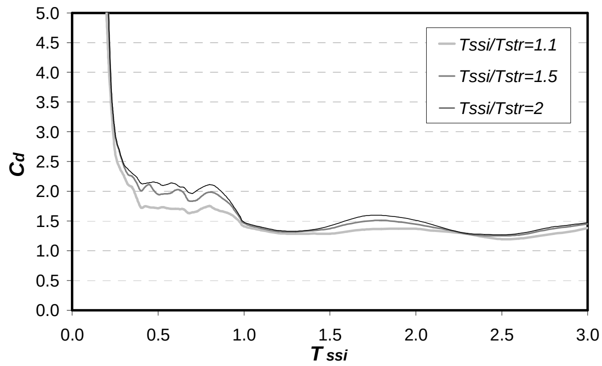
It is observed in Fig. 3 that the effect of R_d on C_d is not the same for soil-structure systems with different aspect ratios and different values of T_{ssi}/T_{str}. The effects of these two key parameters are studied next. Figure 4 depicts the variation of C_d with T_{ssi}/T_{str} for three different values of *h/b*. The results are presented for R_d =4. It can be seen in Fig. 4 that generally for systems with specific period, T_{ssi}, and specific aspect ratio, C_d increases when T_{ssi}/T_{str} becomes larger. In the other words, when the effect of soil-structure interaction increases, systems will experience more displacement, which is mainly because of more rotation due to foundation uplift. This is especially true for squatty buildings with low aspect ratios. However, the effect is not considerable for slender structures with *h/b*=5. The reason backs to the nature of soil-structure systems. It is known that the level of radiation damping due to SSI is much higher for squatty structures in comparison to slender structures [21, 22]. Therefore, the loss of damping due to foundation uplift would be more for squatty structures with larger radiation damping capacity.



(a) *h/b*=1



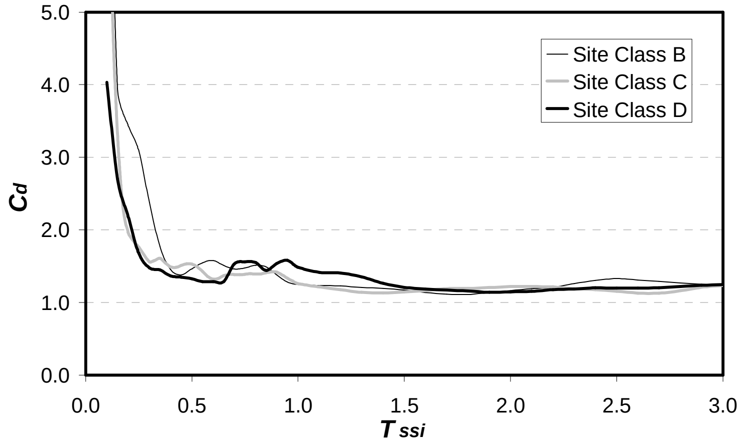
(b) *h/b*=2



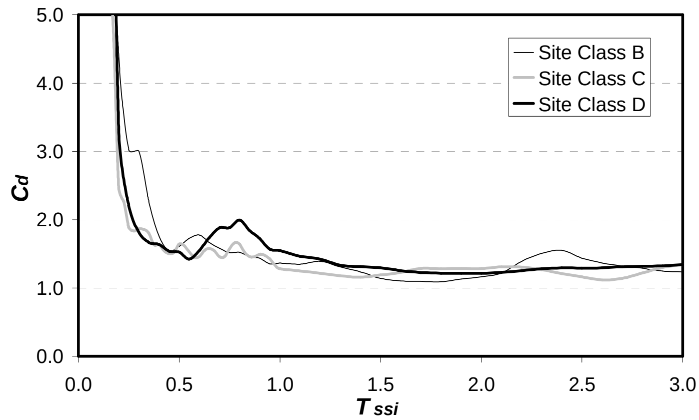
(c) h/b=5

Fig. 4 The effects of T_{ssi}/T_{str} on C_d (R_d=4)

The effect of frequency content of the applied base excitation on resulting displacement ratios is studied next. This is done by comparing the results for ground motions recorded on soil types B and D with those for soil type C. All 20 ground motions provided by FEMA440 [24] for each soil type are used in the study. Figure 5 compares the results for two typical cases of T_{ssi}/T_{str}=1.5, h/b=2, R_d=3 and T_{ssi}/T_{str}=2, h/b=5, R_d=3. As seen the results are almost the same for all soil types for periods larger than 0.5 second. For periods shorter than 0.5 second, however, the results for soil type B can be much larger than the other two soil types. But it should be noted that the latter range of period is not practical for slender structures with h/b=2 and h/b=5. A complete set of results for soil types B and D are depicted in Figs. 6 and 7, respectively. Comparison of these figures with Fig. 3 shows the same trend for all three soil types.



(a) The effects of site class on C_d
(T_{ssi}/T_{str}=1.5, h/b=2, R_d=3)



(b) The effects of site class on C_d
(T_{ssi}/T_{str}=2, h/b=5, R_d=3)

Fig. 5 The effects of site class on C_d

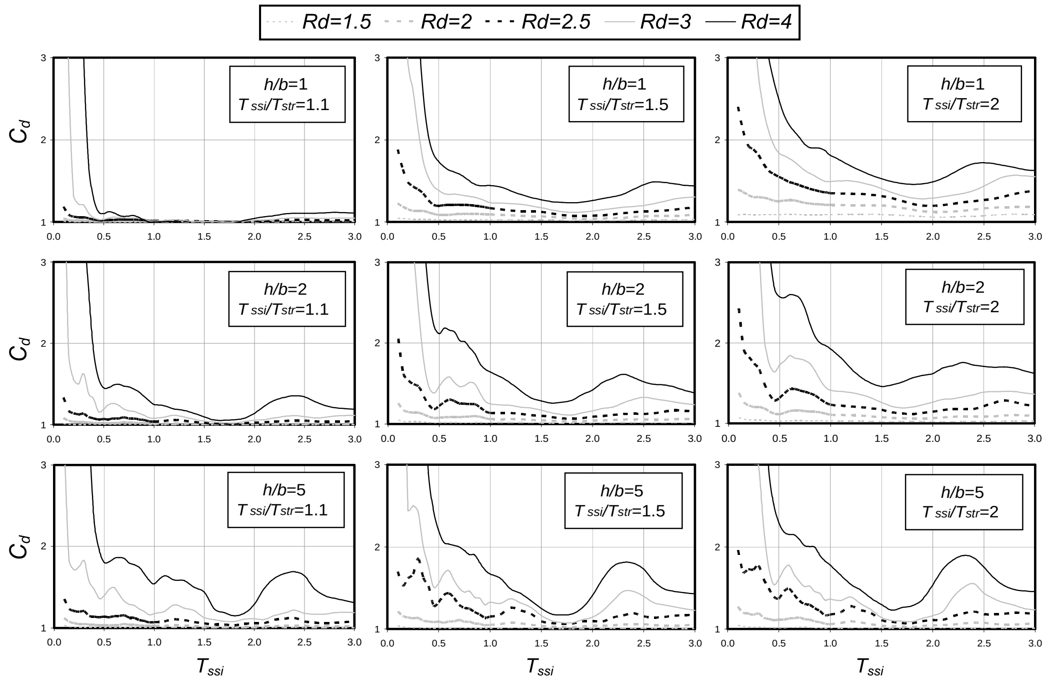


Fig. 6 C_d for different soil-structure systems subjected to the records of site class B

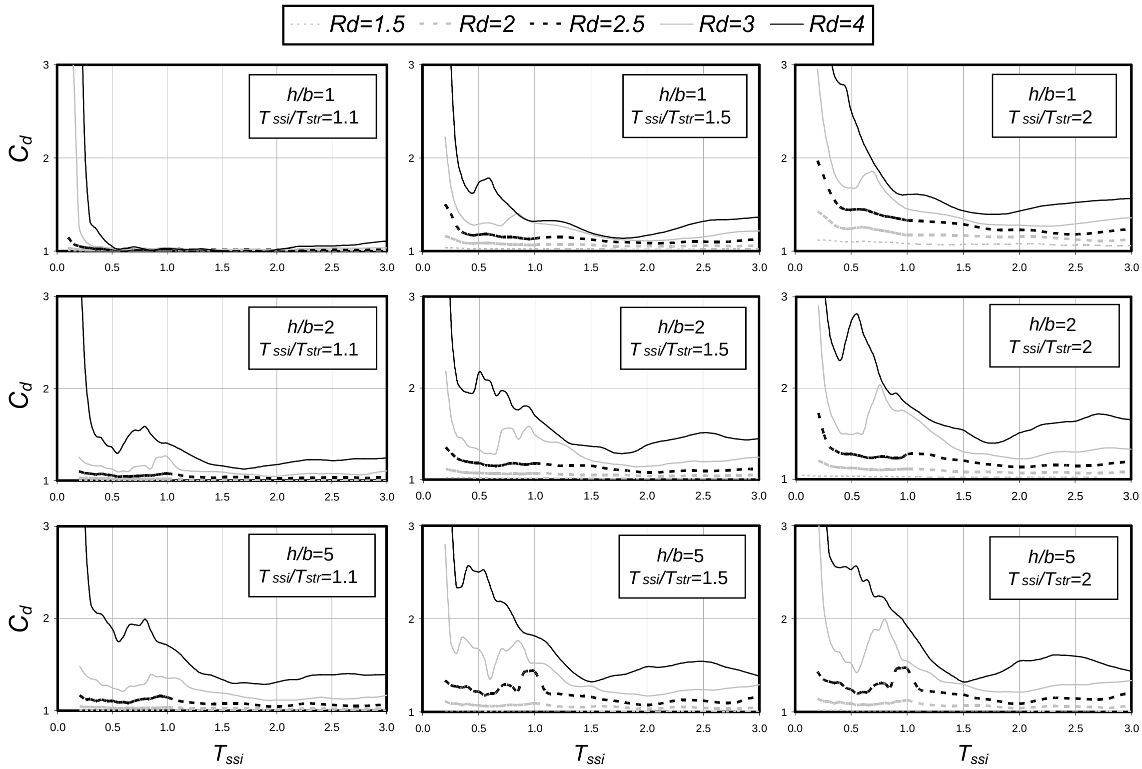


Fig. 7 C_d for different soil-structure systems subjected to the records of site class D

6. Drift of the Structure

In this section the effect of foundation uplift on resulting drift in the super-structure is studied. The results for drift ratios, as defined in Eq. (11), versus the period of the soil-structure system are depicted for soil types B, C and D in Figs. 8 to 10, respectively. In each figure, again, the results are shown for a wide range of non-dimensional key parameters. The results show the same trend of lower drift ratios for uplifting systems for all soil types. The only exception is the rare case of very short period systems with a large uplift index. On the other hand, results show little variation of C_{dr} for systems having periods longer than 0.5 second.

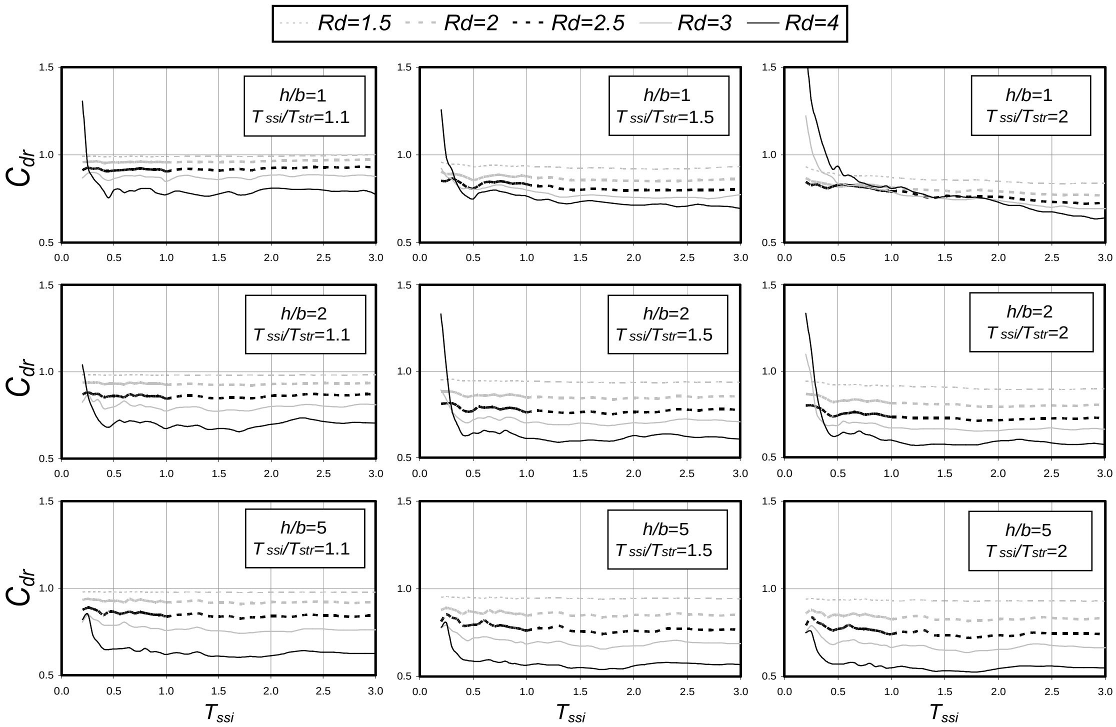


Fig. 8 C_{dr} for different soil-structure systems subjected to the records of site class B

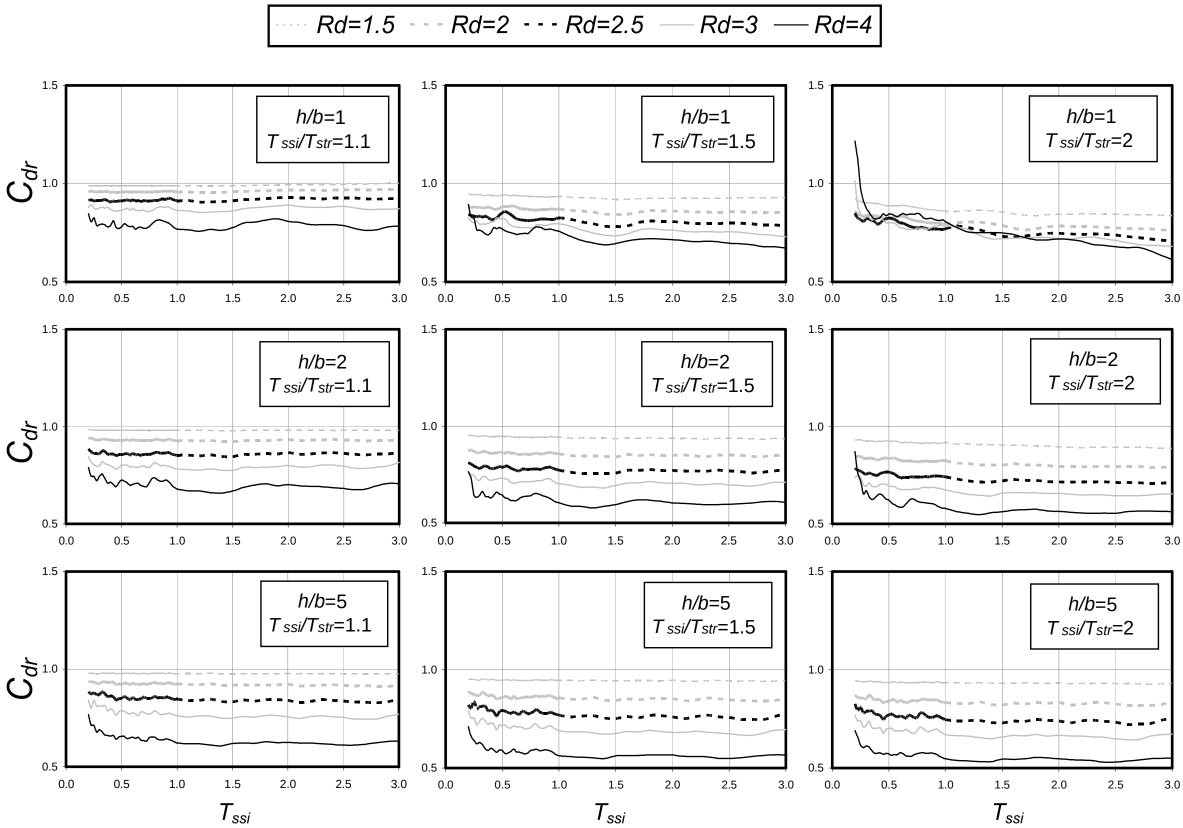


Fig. 9 C_{dr} for different soil-structure systems subjected to the records of site class C

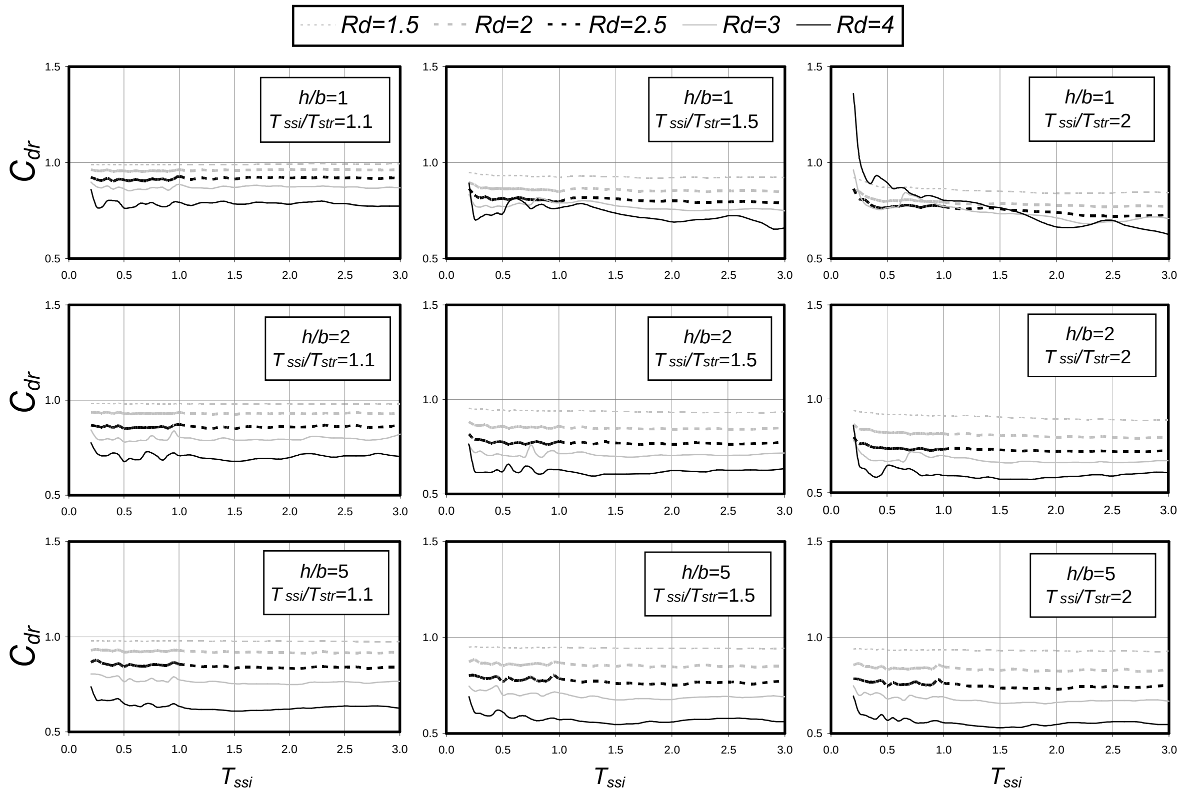


Fig. 10 C_{dr} for different soil-structure systems subjected to the records of site class D

Obviously, more reduction in drift ratio is observed for larger uplift indices. Moreover, increasing T_{ssi}/T_{str} results in more reduction in drift ratio. In the other words, the flexibility of supporting medium helps to reduce the deformation in the structure. Also, the results of Figs. 8 to 10 reveal that slender structures allowed to uplift experience less drift comparing to systems having lower aspect ratio but the same R_d and T_{ssi}/T_{str}. This can be explained by the fact that the effective period of the system is increased due to foundation uplift. As a result, the seismic base shear demand, or in the other words the drift response of the structure, decreases. Since the main source of this period elongation is reduction in rocking stiffness of foundation, the effect becomes more influential for slender systems and consequently the drift ratio for these systems decreases more.

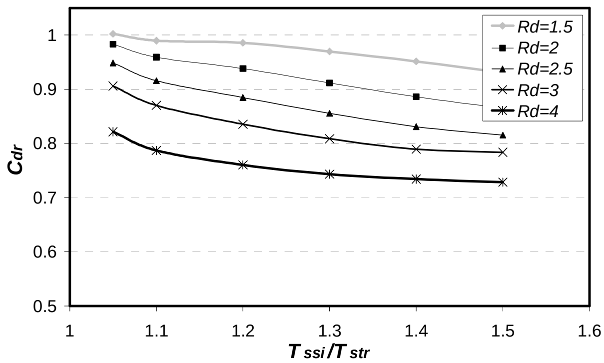
The results of the conducted parametric study provide a general guideline to estimate the effect of foundation uplift on elastic response of the structure for a wide range of soil-structure systems. However, it would be constructive to find when the foundation uplift would be important in real practice. For this purpose, it is needed to identify the practical range of T_{ssi}/T_{str} and R_d parameters for systems with different aspect ratios. It is known that large values of T_{ssi}/T_{str} cannot be expected for conventional short and squatty buildings [21]. On the other hand, R_d is not usually a large value for such buildings. That is because the damping ratio for squatty structures can be very large due to radiation damping in the soil [21, 22], which leads to relatively small elastic strength demand, $(F_{el})_{NoUplift}$. Moreover, P_{iu}, which appears in the denominator of Eq. (9), is relatively large for small values of *h/b*. Therefore, it can be concluded that the effect of foundation uplift should not be important for short period squatty structures. On the other hand, R_d cannot be large enough for long period slender structures because of small ordinate of response spectra in the long period range. Although very large R_d values could be resulted for short period slender structures, it is obvious that such models have no practical importance. Therefore, it is believed that the most important practical cases are those mid-rise buildings; say 5- to 15-story buildings, especially in the direction in which the dimension of foundation is smaller.

As mentioned before, the drift ratio practically remains constant for T_{ssi}>0.5. Also, the results of Figs. 8 to 10 are very similar for different soil types in this range of period. The results show more variation for systems with periods shorter than 0.5 second. However, such short period systems do not exist in reality. Thus, one may conclude the drift ratio is practically independent of system's period and site class. It suggests using the average of results, for periods longer than 0.5 second for all three soil types, to study the effect of *h/b* and T_{ssi}/T_{str} on C_{dr}. The variation of C_{dr} with T_{ssi}/T_{str} is drawn in Fig. 11 for three aspect ratios. Different ranges of T_{ssi}/T_{str} are considered for different aspect ratios to cover practical range of conventional soil-structure systems. In each figure the results are presented for five values of uplift index ranging from 1.5 to 4 corresponding to systems with different level of expected foundation uplift. This figure clearly shows more reduction in drift ratio for more slender systems and for systems with more SSI effect, i.e., larger T_{ssi}/T_{str} ratio. In elastic systems change in the drift is directly related to the resulting base shear of the super-structure. Therefore, Fig. 11 also shows the effect of uplift index on base shear of soil-structure systems.

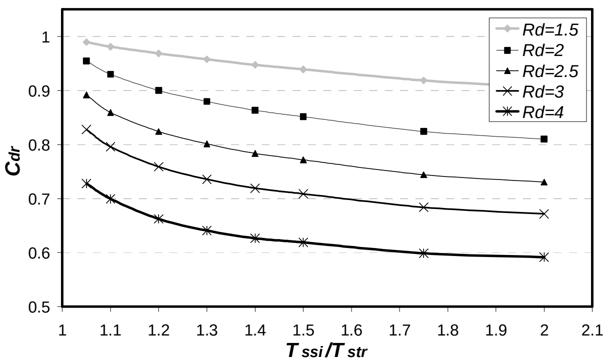
Clear trends of results in Fig. 11 suggest proposing analytical expressions for C_{dr} through regression analysis. Eq. 12 provides a simplified expression for soil-structures systems with periods longer than 0.5 second. The general form of this equation was suggested based on a detailed study on the role of each individual parameter and the coefficients were then evaluated using nonlinear regression analysis to minimize the resulting errors.

$$\frac{1}{C_{dr}}=\left(\frac{0.008(h/b)^2-0.05(h/b)-0.05}{(T_{ssi}/T_{str})^3}-\frac{0.18}{h/b}+0.35\right)R_d+\frac{0.43}{(h/b)^{0.5}}+0.43 \qquad (12)$$

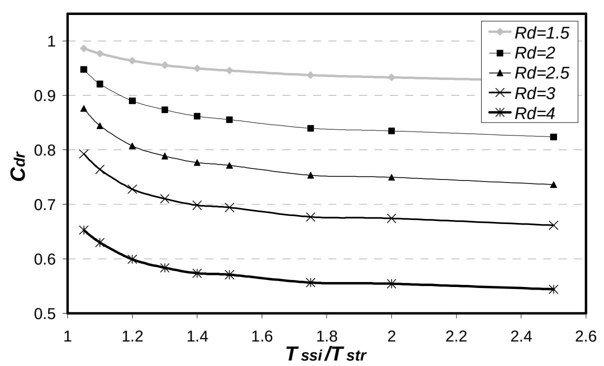
Samples of the fitted curves along with the original data for some typical cases are shown in Fig. 12. It can be seen that the proposed expression captures the computed results for mean values of C_{dr}, presented in Fig. 11, with sufficient accuracy. The mean of errors have been shown in Fig.13.



(a) h/b=1

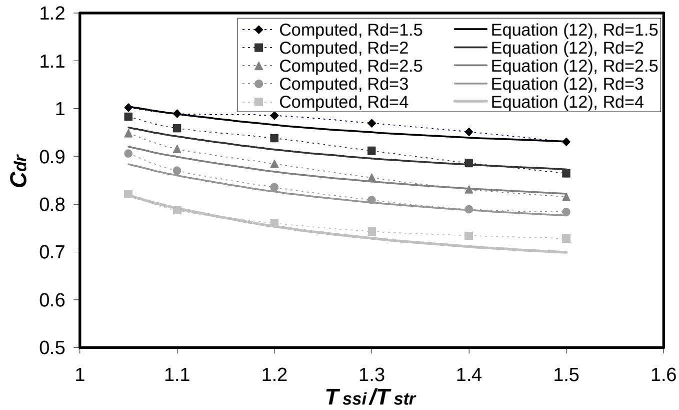


(b) *h/b*=2

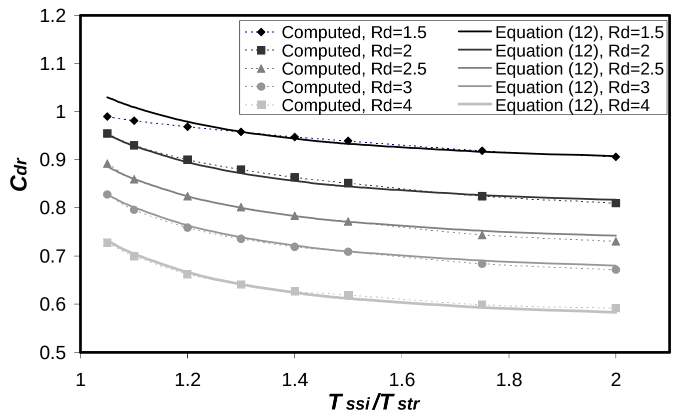


(c) *h/b*=5

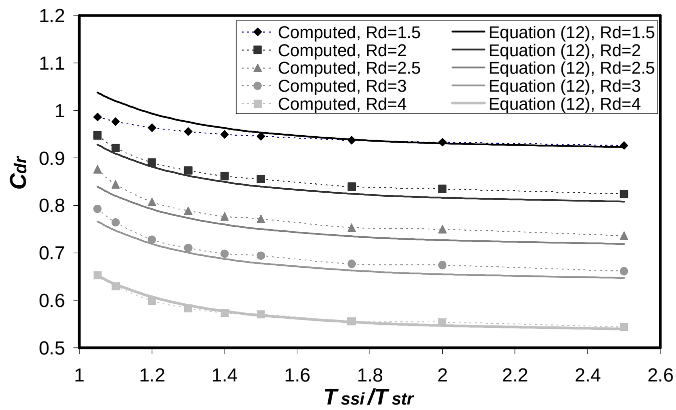
Fig. 11 Mean values of C_{dr} for systems with period larger than 0.5 sec for all site classes



(a) *h/b*=1

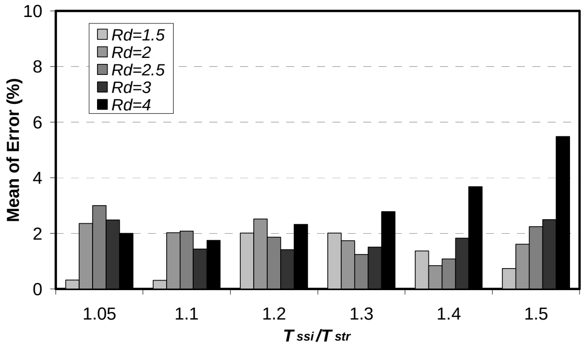


(b) *h/b*=2

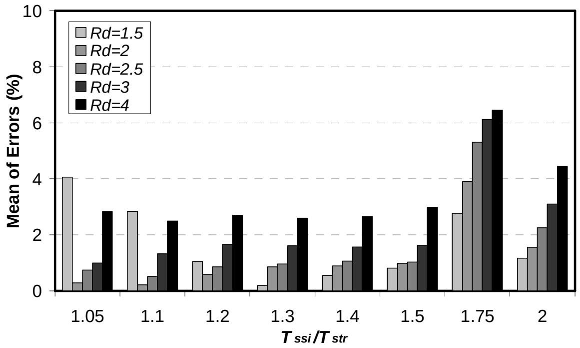


(c) *h/b*=**5**

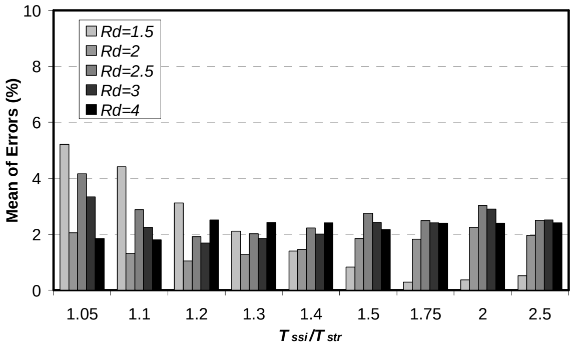
Fig. 12 Comparison of the regressed function of Eq. (12) with the computed exact values for some examples



(a) *h/b*=1



(b) *h/b*=2



(c) *h/b*=5

Fig. 13 Mean of the errors between the regressed function of Eq. (12) and computed exact values

7. Conclusions

The effect of foundation uplift on elastic response of soil-structure systems was investigated. In particular, the uplift effect on the displacement ratio and the drift ratio, as defined in Eq. (10) and Eq. (11), was studied. This is done parametrically by introducing a set of non-dimensional key parameters, which control the response of the system. These parameters are the so-called uplift index as defined in Eq. (9), the aspect ratio of the super-structure and the ratio of the period of the soil-structure system to that of the corresponding fixed-base structure, T_{ssi}/T_{str}. The former parameter defines the level of expected foundation uplift while the latter one is an index for soil-structure interaction severity in the problem.

Obviously, increasing uplift index results in more displacement ratios, which is mainly because of more rotation due to foundation uplift. However, the effect of uplift index on displacement ratio is not the same for soil-structure systems with different aspect ratios and different values of T_{ssi}/T_{str}. Generally speaking, displacement ratio increases by increasing T_{ssi}/T_{str}, especially for buildings with lower aspect ratios. On the other hand, drift ratios decrease due to foundation uplift. Moreover, it was observed that soil-structure systems with more dominant SSI effect, i.e., for larger values of T_{ssi}/T_{str} ratio, and higher aspect ratio experience more reduction in drift of structure. Accordingly, approximate expressions are provided to estimate drift ratios for soil-structure systems. Since the change in drift is directly related to the change of base shear in elastic systems the findings of the paper are readily applicable to the effect of foundation uplift on base shear of soil-structure systems.

At the end, it should be noted that only the global effect of foundation uplift are discussed in this paper. It should be reminded that despite of reduction in base shear several negative local effects can be caused by foundation uplift, which deserve special attention. Damages due to large differential deformations between different parts of the structure, especially in the connections, [26, 27] and repeating impacts between the foundation and soil due to foundation uplift [26, 28] are examples, which could not be account for in the simple model used in this paper.

References

[1] Jennings PC, Bielak J. Dynamics of buildings-soil interaction, Bulletin of Seismological Society of America, 1973, Vol. 63, pp. 9-48.

[2] Veletsos AS, Meek JW. Dynamic behavior of building–foundation systems, Earthquake Engineering and Structural Dynamics, 1974, Vol. 3, pp. 121-138.

[3] Novak M. Effect of soil on structural response to wind and earthquake, Earthquake Engineering and Structural Dynamics, 1974, Vol. 3, pp. 79-96.

[4] Apostolou M, Gazetas G, Garini E. Seismic response of slender rigid structures with foundation uplifting, Soil Dynamics and Earthquake Engineering, 2007, Vol. 27, pp. 642-654.

[5] Housner GW. The behavior of inverted pendulum structures during earthquakes, Bulletin of Seismological Society of America, 1963, No. 2, Vol. 53, pp. 404-17.

[6] Federal Emergency Management Agency (FEMA), Pre-standard and Commentary for the Seismic Rehabilitation of Buildings. FEMA 356, Washington, D.C, 2000.

[7] Psycharis I, Jennings P. Rocking of slender rigid bodies allowed to uplift, Earthquake Engineering and Structural Dynamics, 1983, Vol. 11, pp. 57-76.

[8] Makris N, Konstantinidis D. The rocking spectrum and the limitations of practical design methodologies, Earthquake Engineering and Structural Dynamics, 2003, Vol. 32, pp. 265-289.

[9] Gazetas G, Apostolou M. Nonlinear soil–structure interaction: foundation uplifting and soil yielding, Proceedings of 3rd US–Japan workshop on soil–structure interaction, Menlo Park, California, 2004.

[10] Ishiyama Y. Motions of rigid bodies and criteria for overturning by earthquake excitations, Earthquake Engineering and Structural Dynamics, 1982, Vol. 10, pp. 635-650.

[11] Yim C, Chopra A, Penzien J. Rocking response of rigid

blocks to earthquakes, Earthquake Engineering and Structural Dynamics, 1980, Vol. 8, pp. 565-587.
[12] Meek JW. Effects of foundation tipping on dynamic response, Journal of the Structural Division (ASCE), 1975, Vol. 101, pp. 1297-1311.
[13] Yim C, Chopra A. Earthquake response of structures with partial uplift on winkler foundation, Earthquake Engineering and Structural Dynamics, 1984, Vol. 12, pp. 263-281.
[14] Chopra A, Yim C. Simplified earthquake analysis of structures with foundation uplift, Journal of Structural Engineering (ASCE), 1985, Vol. 111, pp. 906-930.
[15] Oliveto G, Calio I, Greco A. Large displacement behavior of a structural model with foundation uplift under impulsive and earthquake excitations, Earthquake Engineering and Structural Dynamics, 2003, Vol. 32, pp. 369-393.
[16] Khoshnoudian F, Shahreza M, Paytam F. P-delta effects on earthquake response of structures with foundation uplift, Journal of Soil Dynamics and Earthquake Engineering, 2012, Vol. 34, pp. 25-36.
[17] Acikgoz S, Dejong MJ. The interaction of elasticity and rocking in flexible structures allowed to uplift, Earthquake Engineering and Structural Dynamics, Published online in Wiley Online Library (wileyonlinelibrary.com) DOI: 10.1002/eqe.2181, 2012.
[18] Wolf J. Foundation Vibration Analysis Using Simple Physical Model, Prentice-Hall, Inc, Englewood Cliffs, N.J, 1994.
[19] American Society of Civil Engineers (ASCE), Standard for Seismic Rehabilitation of Existing Buildings, ASCE 41-06, Virginia, 2007.
[20] American Society of Civil Engineers (ASCE), Minimum Design Loads for Buildings and Other Structures, ASCE 7-10, Virginia, 2010.
[21] Ghannad MA, Fukuwa N, Nishizaka R. A Study on Frequency and Damping of Soil-structure Systems Using Simplified Model, Journal of Structural Engineering (AIJ), 1998, Vol. 44B, pp. 85-93.
[22] Veletsos AS. Dynamics of Structure-foundation Systems, In Structural and Geotechnical Mechanics, Hall WJ. (Ed.), Prentice Hall, New Jersey, 1977.
[23] Applied Technology Council (ATC), Tentative Provisions for the Development of Seismic Regulations for Buildings, ATC 3-06, California, 1978.
[24] Federal Emergency Management Agency (FEMA), Recommended Provisions for Improvement of Nonlinear Static Seismic Analysis Procedures, FEMA 440, Washington D.C, 2005.
[25] OpenSees (Open System for Earthquake Engineering Simulation platform), developed by the Pacific Earthquake Engineering Research Center (PEER), at the University of California, Berkeley. http://opensees.berkeley.edu/.
[26] Meek JW. Dynamic response of tipping core buildings, Earthquake Engineering and Structural Dynamics, 1978, Vol. 6, pp. 437-454.
[27] Applied Technology council (ATC), Seismic Evaluation and Retrofit of Concrete Buildings. ATC-40, Applied Technology Council, Redwood City, California, 1996.
[28] Harden CH, Hutchinson T, Martin GR, Kutter BL. Numerical Modeling of the Nonlinear Cyclic Response of Shallow Foundations, Report No. PEER 2005/04, Pacific Earthquake Engineering Research Center, 2005.