A New Uplift Foundation Analysis Model to Simulate Dynamic Nonlinear Soil-Structure-Interaction

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SUMMARY:
In the field of earthquake engineering, soil-structure interaction is an important phenomenon that has to be taken into account. For example, for evaluating dynamic characteristics of slender structures like tall buildings or school buildings, it is necessary to consider the effect of uplift of the foundation. In this paper, a new nonlinear analysis model is proposed. By adopting this new model, it is able to calculate the response of the building considering the geometrical nonlinearity of the connections (uplift) between the structure and the ground under strong ground motions. This model also takes into account the stiffness of the soil. The effect of nonlinear behaviour of the foundation on the response of the superstructure is studied in this paper.

Keywords: Soil-Structure Interaction, Geometrical Nonlinearity, Impedance, Uplift Motion, MDOF System

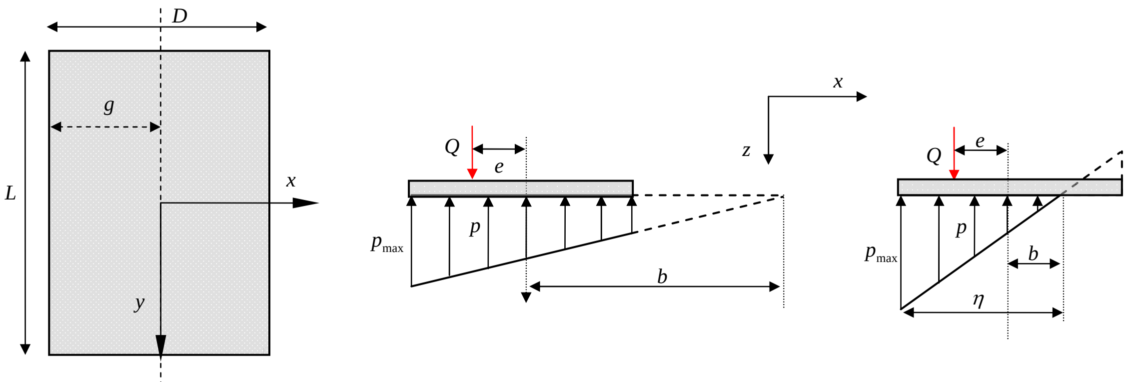
1. INTRODUCTION

In the field of earthquake engineering, soil-structure interaction is an important phenomenon that has to be taken into account to reproduce correctly the non-linear behaviour of a structure and thus to be able to predict the response of existing building during the seismic excitation. When designing slender buildings, it is necessary to define the characteristics of the soil, the structure and the connection between them. It is obvious that the behaviour will be different if the foundation of the structure is embedded in the soil or just fixed. When it comes to the actual situation, it is important for the designers to grasp the behaviour of buildings during the seismic excitation. For example, during the earthquake, the damage of low-rise RC buildings is not so large compared with that of the other types of buildings (Hayashi, 1996; Sugimoto *et al.*, 2008). Some slip and uplift phenomenon of the low-rise RC buildings are noticed after the earthquake. Due to the slip and uplift of the foundation, the response of the structure will be changed. It is necessary for the researchers to simulate the response of the structure considering the real behaviour of the foundation. Simulating the uplift phenomenon involves detailed 3D meshes for the soil and the structure, adding the springs and dashpot to simulate the connection between the foundation and the soil, a big number of degrees of freedom and thus huge computational costs. In order to avoid the huge work caused by the meshing of the soil and the structure, some simplified foundation models are proposed (Fukuwa et al., 1986; Song *et al.*, 1993). Though the existing simplified foundation models just consider the uplift phenomenon in one direction, they can not take into account the effect of response in the other direction due to the uplift phenomenon. In order to solve the coupled phenomenon of the uplift in the two horizontal directions at the same time, a new simplified model is proposed considering the connection between the foundation and the soil around it. It takes into account the uplift of the foundation in the two horizontal directions at the same time. An extension of this proposed model is introduced hereafter.

The paper starts with a brief instruction of the proposed model, and then the proposed model is implemented into a MDOF system, and the performance of the structure obtained from using the proposed model is compared with that of the structure obtained from adopting the SR (Sway-Rocking) model. A reduction of the response of the superstructure when the uplift phenomenon happens is found through this research.

2. MATHEMATICAL DESCRIPTION OF THE UPLIFT MECHENISM

As an example of a soil-structure-interaction analysis with geometrical nonlinearities occurrence, a rigid foundation which can uplift, resting on the surface of a half-space (see Fig. 2.1) is examined. In practice, it is difficult to describe the distribution of the subgrade reaction in an accurate way, for an approximate description of the subgrade reaction of the foundation, linear distribution assumption is employed. The mechanism presented hereafter describes in a realistic logical way uplift using a unique state variable η as the variation of the connection between the foundation and the half-space. In the following, the symbols Q and e are used to define the weight of the upper-structure and the eccentric distance respectively. The meaning of the other symbols can be referred to Fig. 2.1.



(a) Plane graph of the foundation (b) No uplift (c) Uplift

Figure 2.1 The distribution of subgrade reaction

The mathematical expression of the subgrade reaction (optional position) is provided by Eqn. (2.1). Based on Eqn. (2.1), the balance equation in the vertical direction z is therefore given by Eqn. (2.2). Meanwhile the balance equation in the rotation direction of y axis is introduced as Eqn. (2.3). It is obvious that the eccentric distance *e* and the variable b can be obtained according to the equations from (2.1)~(2.3), as shown in Eqn. (2.4) and Eqn. (2.5).

$$p = \frac{p_{\max}}{b+g}(b-x) \tag{2.1}$$

$$Q = \int_A p dA = \frac{p_{\max}}{b+g}\left(b\int_A dA - \int_A x dA\right) \tag{2.2}$$

$$Qe = -\int_A p x dA = \frac{p_{\max}}{b+g}\left(-b\int_A x dA + \int_A x^2 dA\right) \tag{2.3}$$

$$e = \frac{\int_A x^2 dA - b\int_A x dA}{b\int_A dA - \int_A x dA} \tag{2.4}$$

$$b = \frac{e\int_A x dA + \int_A x^2 dA}{e\int_A dA + \int_A x dA} \tag{2.5}$$

In order to find the relation between the variable b and the eccentric distance *e*, two cases should be studied. One case is to investigate the relation when there is no uplift phenomenon during the seismic excitation. The other one is to determine the change of the relation if the uplift phenomenon happens. In the case of rectangle foundation, when there is no uplift, the relationship is given by Eqn. (2.6), on the opposite hand, the equation of the relationship is provided by Eqn. (2.7). Through Eqn. (2.7), the relationship between the variable η and the eccentric distance e can be obtained (as shown in Eqn.(2.8)). That means through calculating the eccentric distance e the variable η can also be gained. If we can find the relation (which will be introduced in section 3) between the variable η and the impedance of the foundation, the instantaneous impedance of the foundation during the seismic excitation can be calculated.

$$b = \frac{D^2}{12e} \tag{2.6}$$

$$b = D - 3e \tag{2.7}$$

$$\eta = 3D(\frac{1}{2} - \frac{e}{D}) \tag{2.8}$$

3. GENERAL DESCRIPTION OF THE PROPOSED MODEL

This section describes briefly the variables and theories taken into account by the proposed model. For more information the reader is invited to look in Sugimoto *et al.* (2010).

3.1. The analysis procedure of the proposed model

As the connection area between the foundation and the soil varies when the uplift phenomenon happens, the impedance of the foundation also changes. To study the variation of the foundation impedance, a connection model as shown in Fig. 3.1 is proposed. The proposed model is composed of six springs and six dashpots in the three dimensions space. The variable η is calculated from the eccentric distance *e* of the foundation. The variation in the each direction of the impedance depends on the pre-mentioned connection area. That means if the uplift happens in one direction, the impedance of the other direction will also change, and the uplift in the two horizontal directions is coupled strongly.

To discuss the variation of the impedance affected by the change of the connection area, a new process of describing the variation of the connection area is proposed (Sugimoto *et al.*, 2008), as shown in Fig. 3.2. The variation of the impedance is obtained by a simple two-step procedure:

(1) As a first approximation, the connection area before and after uplift is equal to a square A_0 and A_1 separately. The impedance of the equivalent square A_0 is calculated through the Thin Layered Method, and the impedance of the equivalent square A_1 is obtained from the original equivalent square A_0 by using compensation factors α , β (see section 3.2).

(2) The impedance of the foundation after uplift is obtained from the impedance of the equivalent square A_1 by employing another compensation factor λ (see section 3.2).

3.2. Compensation factors of the impedance

According to the new process explained in section 3.1, a compensation factor of the impedance in each direction can be obtained based on the Thin Layered Method. The formulation of the compensation is shown in Table 3.1. α and β refer to the reduction ratio of the width and length of the foundation respectively. If the impedance of a square foundation is obtained through the Thin Layered Method, the impedance of an arbitrary foundation can be calculated by multiplying these compensation factors. That means by multiplying the compensation factor, we can get the impedance of the foundation at every time step even if the uplift phenomenon of the foundation occurs.

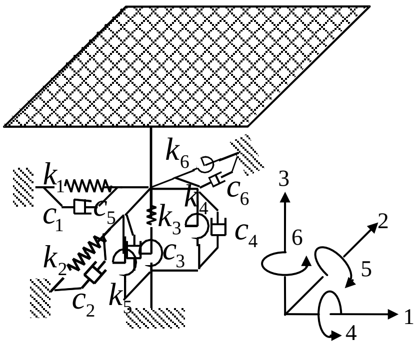


Figure 3.1 Proposed model

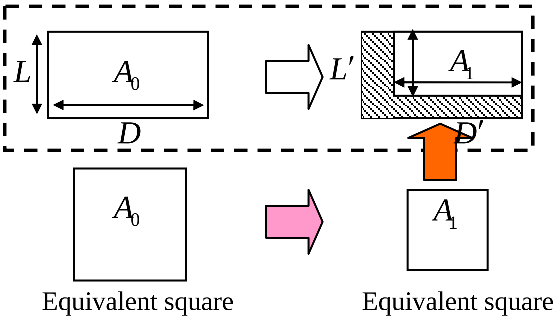
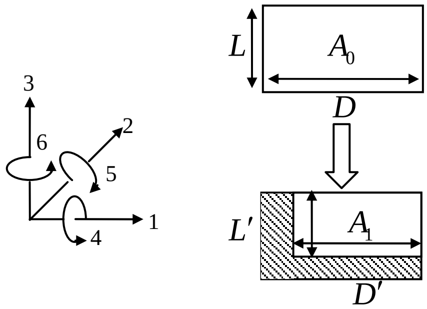


Figure 3.2 Variation of the connection area

Table 3.1 Compensation factor of the impedance

Real	K_{11}	$\gamma=\sqrt{\alpha\beta}\left(0.55\lambda^{0.37}+0.45\lambda^{-0.31}\right)$
	K_{22}	$\gamma=\sqrt{\alpha\beta}\left(0.48\lambda^{0.28}+0.52\lambda^{-0.38}\right)$
	K_{33}	$\gamma=\sqrt{\alpha\beta}\left\{0.205\left(\sqrt{\lambda}+1/\sqrt{\lambda}\right)+0.59\right\}$
	K_{44}	$\gamma=\sqrt{\alpha\beta}^{3}\times\lambda^{0.61}$
	K_{55}	$\gamma=\sqrt{\alpha\beta}^{3}\times\lambda^{-0.86}$
	K_{66}	$\gamma=\sqrt{\alpha\beta}^{3}\times 0.49\left(\lambda+1/\lambda\right)$
Imag.	C_{11}	$\gamma=\sqrt{\alpha\beta}^{2}$
	C_{22}	$\gamma=\sqrt{\alpha\beta}^{2}$
	C_{33}	$\gamma=\sqrt{\alpha\beta}^{2}$
	C_{44}	$\gamma=\sqrt{\alpha\beta}^{4.35}\times\lambda^{1.06}$
	C_{55}	$\gamma=\sqrt{\alpha\beta}^{4.35}\times\lambda^{-1.05}$
	C_{66}	$\gamma=\sqrt{\alpha\beta}^{4.3}\times 0.66\lambda^{-0.9}(\lambda<0.6)$ $\gamma=1.0(\lambda\geq 0.6)$



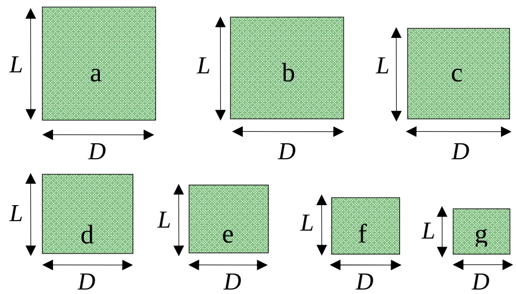
$$\alpha=\frac{L'}{L}\qquad\beta=\frac{D'}{D}\qquad\lambda=\frac{\alpha L}{\beta D}$$

3.3. Correctness of the compensation factor of the impedance

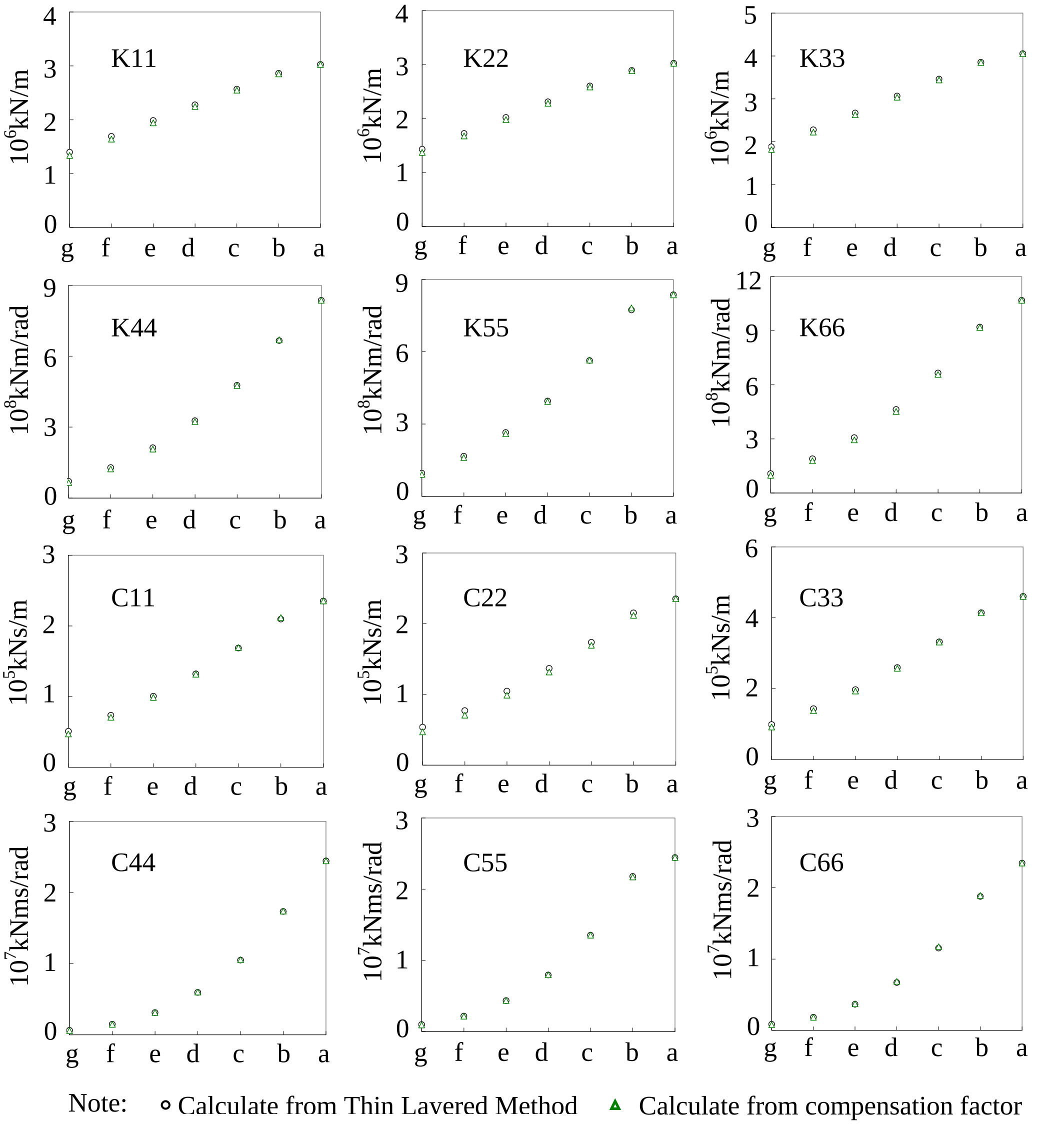
In order to verify the correctness of the proposed compensation factors of the impedance, the impedances of the foundation of different shapes (see Table 3.2) are calculated through the proposed compensation factors and Thin Layered method (H. Tajimi *et al.*, 1976; H. Tajimi, 1984), and then the calculated impedances are compared(see Fig. 3.3). For the calculation by using the proposed method, the impedance of the foundation 30m×30m is calculated through Thin Layered Method, and the

Table 3.2 Parameter of the foundation

Type	L	D	α	β
a	30	30	1.0	1.0
b	27	30	1.0	0.9
c	24	27	0.9	0.8
d	21	24	0.8	0.7
e	18	21	0.7	0.6
f	15	18	0.6	0.5
g	12	15	0.5	0.4



Note: The shear wave velocity of the soil is 150m/s.



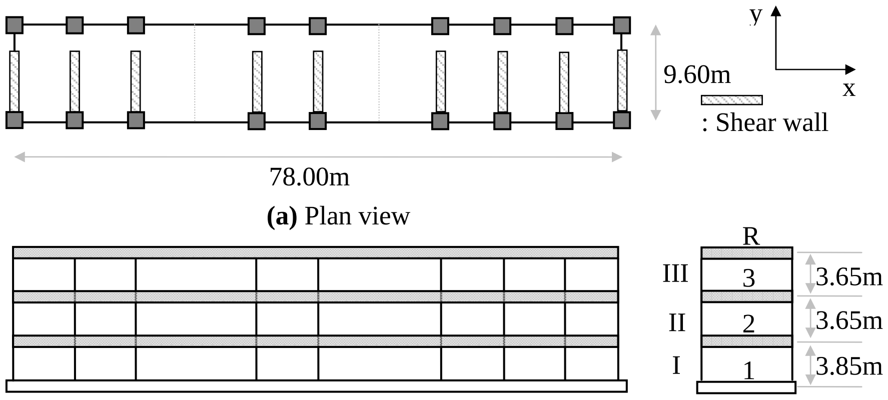
K11~K66: The real part of the impedance calculated at 0.1Hz in the frequency domain.
C11~C66: The imaginary part of the impedance calculated at 2.0Hz in the frequency domain. (Sugimoto *et al.*, 2008)

Figure 3.3 Variation of the connection area

impedance of the other type of foundations is calculated by multiplying the proposed compensation factors. Through the results shown in Fig. 3.3, we can find that the impedances obtained through the above-mentioned methods are identical, which means the correctness of the compensation factors of the impedance can be totally trusted.

4. NUMERICAL SIMULATION OF A MDOF SYSTEM BY USING THE PROPOSED MODEL.

The simulation of the response of a MDOF system is presented hereafter in order to evaluate the efficiency of the proposed model for predicting the behaviour of a low-rise RC building submitted to strong ground motions. To derive the prediction of the damage of low-rise RC buildings under seismic excitation, an existing elementary school building in Japan is examined in this section. The object low-rise RC building rests on a half-space with the shear wave velocity at 150m/s. The dimensions of the foundations and the parameter of the structure are given in Fig. 4.1 and Tab. 4.1. Lumped masses are considered on each floor, taking into account the mass of the corresponding slab and the upper and



(a) Plan view

(b) Elevation view (length direction) **(c)** Width direction

Figure 4.1 A draft of the analyzed school building

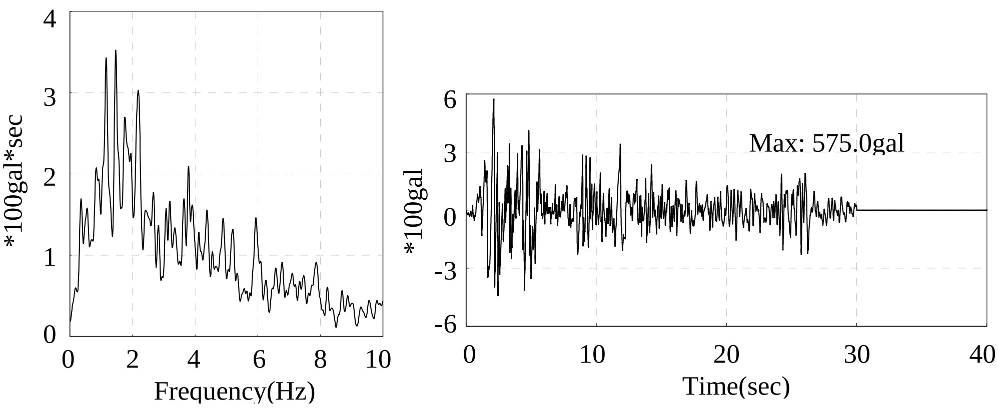


Figure 4.2 Input ground motion and its Fourier spectrum

Table 4.1 Parameters of the analyzed building

Layer	Damping factor	Shear Stiffness(N/m)		Floor	Mass	Inertia Moment(kg*m^2)		Height
		x	y		(kg)	x	y	(m)
III	0.03	4.27×10^9	6.42×10^9	R	7.22×10^5	3.66×10^8	5.55×10^6	11.15
II	0.03	4.27×10^9	6.19×10^9	3	8.21×10^5	4.16×10^8	6.31×10^6	7.50
I	0.03	4.27×10^9	6.08×10^9	2	8.21×10^5	4.16×10^8	6.31×10^6	3.85
				1	8.21×10^5	4.16×10^8	6.31×10^6	0.00

Table 4.2 Hysteretic properties (length direction)

Layer	k_1	k_2	k_3	up_1	up_2
	N/m	N/m	N/m	m	m
III	5.3×10^9	2.1×10^9	5.3×10^7	3.2×10^{-4}	8.6×10^{-3}
II	5.2×10^9	2.1×10^9	5.2×10^7	3.2×10^{-4}	8.6×10^{-3}
I	5.2×10^9	2.1×10^9	5.2×10^7	3.2×10^{-4}	8.6×10^{-3}

Table 4.3 Hysteretic properties (width direction)

Layer	k_1	k_2	k_3	up_1	up_2
	N/m	N/m	N/m	m	m
III	6.4×10^9	2.4×10^9	6.4×10^7	3.0×10^{-3}	1.7×10^{-2}
II	6.2×10^9	2.3×10^9	6.2×10^7	2.9×10^{-3}	1.6×10^{-2}
I	6.1×10^9	2.3×10^9	6.1×10^7	2.8×10^{-3}	1.5×10^{-2}

lower part of the wall. Through the push-over analysis, the nonlinearity of the superstructure can be obtained and the obtained parameters are given in Tab. 4.2 and Tab. 4.3. In this section, a Normal Tri-linear model is used to describe the hysteretic properties of the super-structure. Furthermore, the proposed model is employed in order to simulate the geometric nonlinearity of the foundation during the seismic excitation.

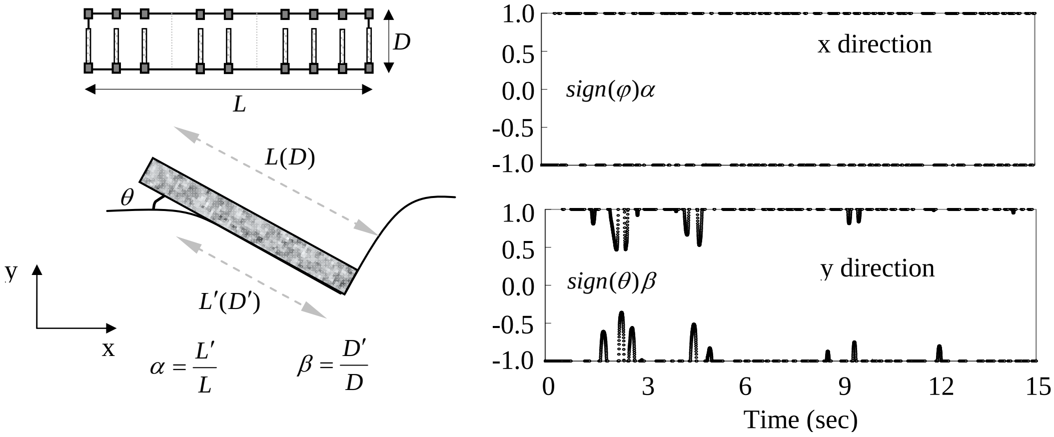
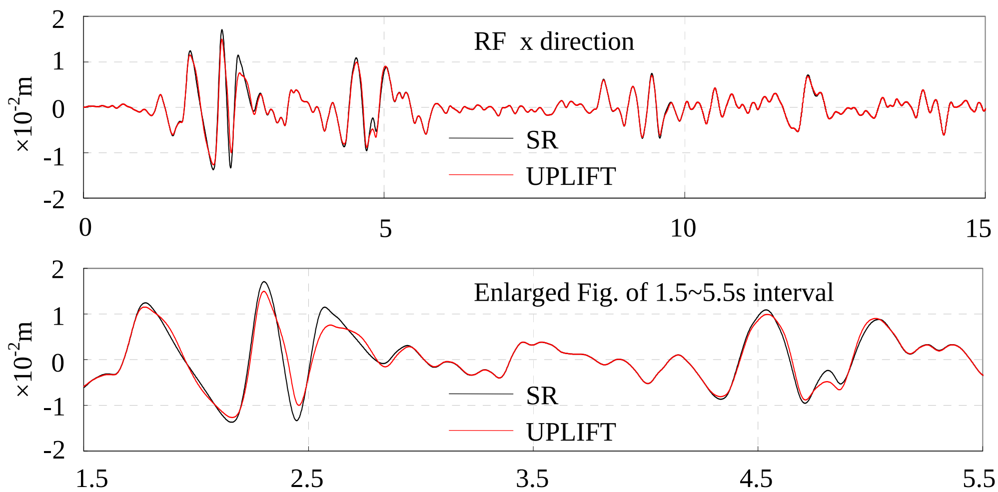
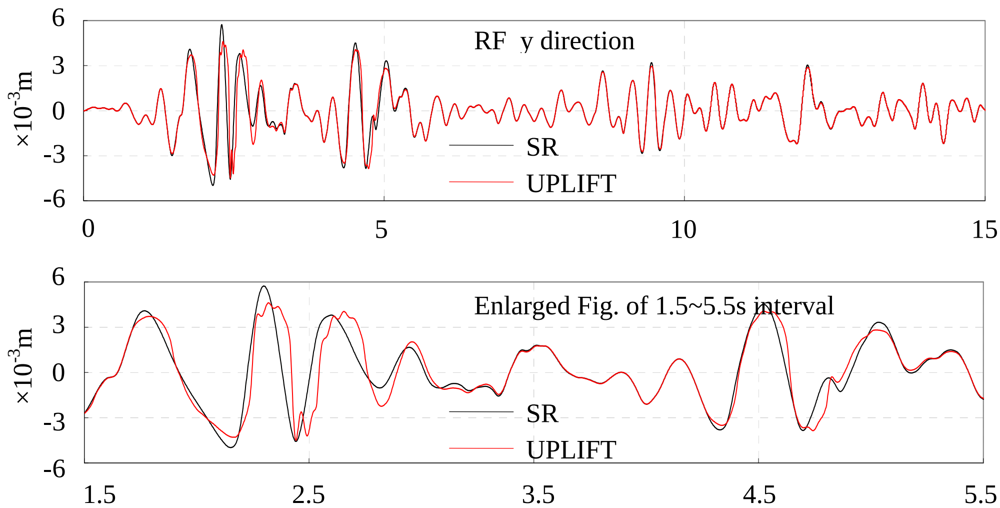


Figure 4.3 Contact ratio of the foundation

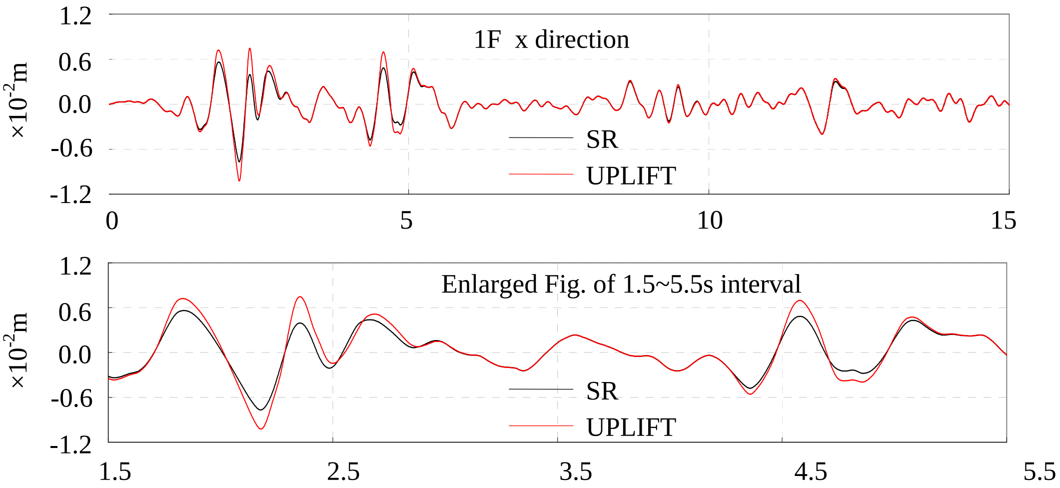


(a) Displacement response of roof (x direction)

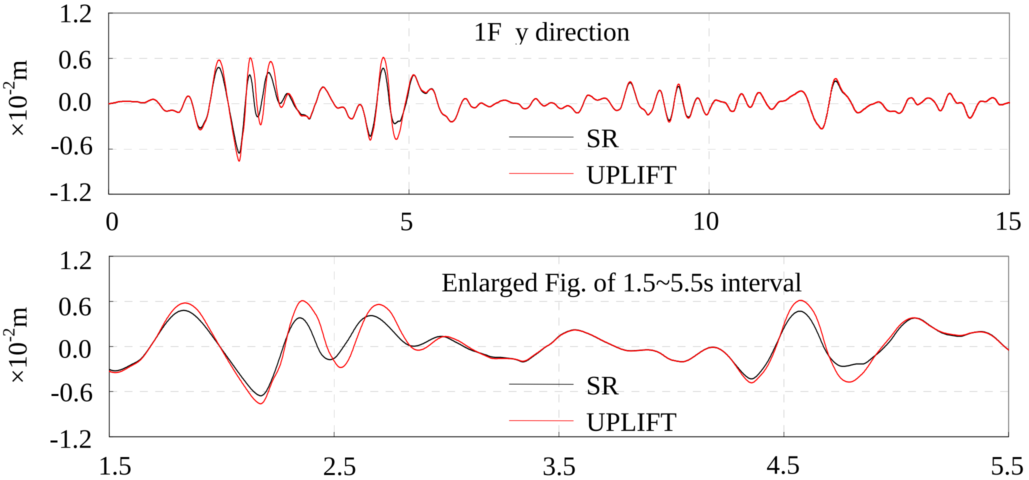


(b) Displacement response of roof (y direction)

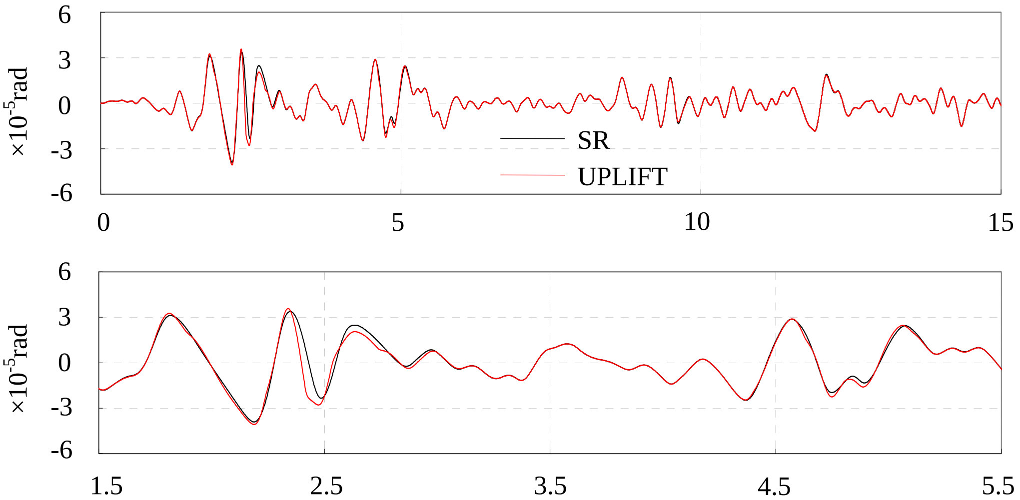
Figure 4.4 Displacement response of roof floor in the horizontal directions (Relative to the 1st floor)



(a) Displacement response of 1st floor (x direction)

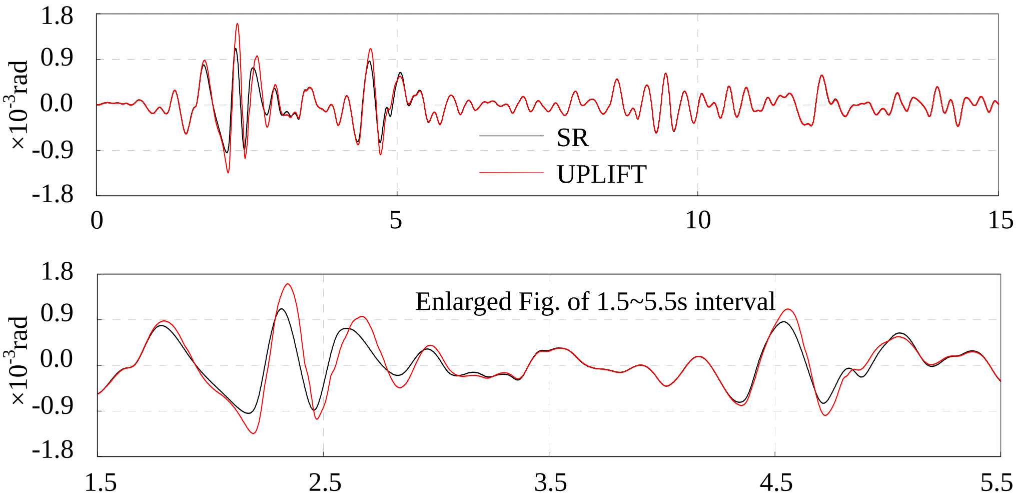


(b) Displacement response of 1st floor (y direction)



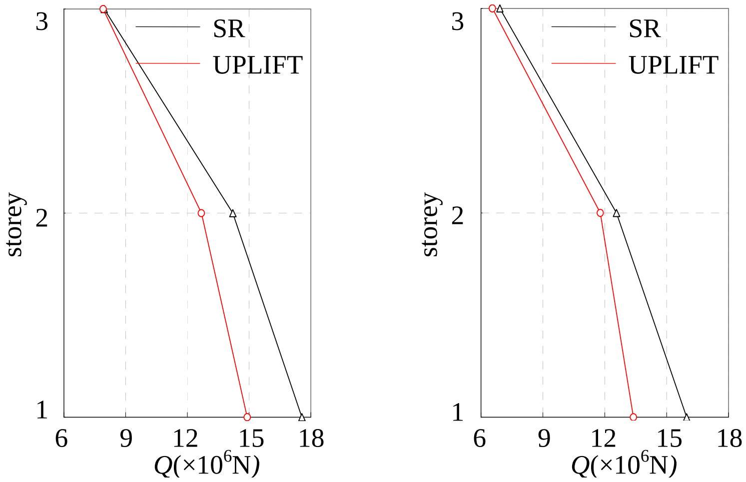
(c) Rotational response (θ) of 1st floor (x direction)

Figure 4.5 Sway and rocking responses of 1st floor



(c) Rotational response (θ) of 1st floor (y direction)

Figure 4.5 Sway and rocking responses of 1st floor (continue)



(a) x direction

(b) y direction

Figure 4.6 Maximum story shear force distribution

The input ground motion (1.7 times EL_Centro_NS acceleration record is used in order to coincide with the Level 2 earthquake design ground input motion in Japan which's maximum velocity is at 50 cm/s) and its Fourier spectrum in the two horizontal directions are shown in Fig. 4.2. Two cases (The model is vibrated in both x and y direction at the same time) are taken into account shown as follows:

SR: Calculating the response of the structure using Sway-Rocking model.

UPLIFT: Calculating the response of the structure using the proposed model.

Through the simulation results between SR and UPLIFT, the uplift mechanism of the foundation during the seismic excitation becomes clear. The results obtained from UPLIFT can be used in order to examine whether the uplift is one of the reasons for the low damage of low-rise RC buildings.

The calculated contact ratio of the foundation in the horizontal two directions is shown in Fig. 4.3. We can see that during the seismic excitation, the uplift phenomenon happens in the y direction, and there is no uplift in the x direction. The simulated displacement response of the roof floor of the low-rise RC building by using two different foundation models is shown in Fig. 4.4. Through analyzing Fig. 4.4, we can find that when the uplift phenomenon happens in the y direction, not only the response of building along the y direction changes, the response of building along the x direction also changes.

The reason for the reduction of the response in the non-uplift direction is that: when the uplift happens in the y direction, the connection area between the foundation and the soil decreases, and the variable of the connection area will lead to the change of the impedance in both horizontal directions. Through Fig. 4.4, we can also find that when the uplift happens, the response of the roof floor shows a decrease trend. The reason for this decrease phenomenon is that when the response of the foundation in the sway and rocking direction increase (see Fig. 4.5), the deformation of the super-structure will be restrained.

The calculated response of the foundation is shown in Fig. 4.5. Through Fig. 4.5 we can see that, when uplift happens, because of the reduction of the impedance during the seismic excitation, the response of the foundation in the sway and rocking direction shows an upward trend. Even though there is no uplift in the x direction, due to the strong coupled phenomenon of the impedance in the horizontal two directions, the response of the foundation also changes.

The maximum story shear force distribution during the seismic excitation is shown in Fig. 4.6. We can know that when the uplift phenomenon happens, the maximum story shear force decreases. It is possible to say that uplift phenomenon is one of the reasons for the low damage of low-rise RC buildings.

5. CONCLUSION

(1) Correctness of the proposed new uplift foundation model is examined. Through this study we can find that the new uplift foundation model can be totally trusted to simulate the geometrical nonlinearity (uplift) of the foundation during the seismic excitation.
(2) In this study, if the uplift occurs, the response of super-structure decreases. Meanwhile the response of the foundation shows an upward trend. It means the response of the super-structure could be decline due to the uplift occurring between the foundation and the soil.
(3) Even though there is no uplift in one horizontal direction, if uplift phenomenon happens in the other horizontal direction, due to the strong coupled phenomenon of the impedance in the horizontal two directions, the response of the super-structure and foundation in the non-uplift direction will also change during the seismic excitation.

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