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*Original Article*

# A Study of the Flexibility Response of Soil Elements on Uplifting Elastic Foundation during Seismic Motion

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***Abstract*** *- This study investigated the influence of soil flexibility on the elastic foundation during uplifting from earthquake ground motion. Foundation flexibility and uplift are occurrences from ground motions that could cause significant changes to system responses, considering the Winkler Foundation with its limitations and the Filonenko-Borodich (F-B) foundation to overcome the limitations of the Winkler foundation. During uplift, the foundation becomes nonlinear as the soil elements yielding becomes more flexible, reducing the ductility of the soil structure system. El-Centro (1940) ground motion in the time domain was used, and differential equations describing motions of the system due to earthquake excitations were developed for the time history analysis with deformations outside the loaded part of the foundation considered. Analyses were performed using Newton's second law of motion, by dynamic equilibrium method like D'Alembert's principle and by applying equilibrium of moments for the equations of motion. The formulated differential equations were solved by applying the Duhamel integral and further solved using Simpson's numerical method. The resulting response effect of the F-B model was discussed in comparison with the Winkler model. The numerical case study was used to illustrate the effects of soil flexibility on elastic foundation and soil ductility during ground motion, which, when neglected, may lead to errors in predicting seismic actions. The structure's response during uplift may differ from the response before uplift, which might depend on the parameters of the structure foundation and intensity of excitation that might determine if structure uplift is beneficial.*

***Keywords*** *- Earthquake, Elastic foundations, Natural frequency, Soil flexibility, Structure.*

## 1. Introduction

The intensity of earthquake ground motion is based on several subjective interpretations. One of the two main factors is the shaking produced at certain locations. The second factor is the effect on people and their observations of damages to structures and the environment around them caused by the quake [1]. The main challenge with earthquakes is that ground motion acceleration varies a lot with time and is quite sporadic. However, foundation flexibility and uplift (i.e. separation between the building foundation and soil) is important for some types of buildings, especially if the probable ground motions are exceeded. Thus, allowing uplift and soil flexibility could change the fundamental period of the system and lead to significantly different responses under seismic forces [2, 3]. It is necessary to understand how soil and structure interact with each other in response to a structure subjected to ground motion and to know how uplift affects structures' dynamic response and safety. This is attributed to the assumption that the soil underlying the structure is perfectly rigid and the structural foundation is firmly bonded to the soil. In reality, this assumption has two deficiencies. Firstly, soils are not infinitely stiff. They have very low tensile stress [4]. Second, many structural foundations are not bonded perfectly to the ground. Gravity force is the only source of bonding force. However, most work on soil-structure interaction was based on the assumption that foundations are firmly bonded to the soil. These two reasons make it possible for structures to uplift when their foundation moves [5] and enable designers to evaluate the real response during ground motion, which this response depends on the soil-structure parameters and ground motion intensity [6, 7].

Typically, soil flexibility is generally not included during design analysis, resulting in grave consequences considering soil-structure interactions. Soil flexibility has been known to cause an increase in natural period and a decrease in stiffness during uplifting, which then alters the seismic response of the structure. This makes it a necessary factor to be considered during design [2], as the natural vibration period helps understand forces acting on structures during uplift. With the uplift of foundations being rarely observed as it is expected to be small and the foundation-soil interface often inaccessible for observation [8], the weight of the structural members resists the earthquake forces by using unnecessary dead weight, large base mat projections, and even artificial anchoring schemes [9]. The soil-structure interaction response effects of structures have been studied by many researchers. Psycharis and Jennings [10], in their work on foundation flexibility and energy dissipation using two spring foundations and the Winkler foundation, concluded that their analysis showed an increased angle of rotation of the foundation mat from an uplift occurrence. Not too clear effects on structural deflections and resulting stresses as foundation uplifting can cause a reduction in the structural responses and an increase in the structural response, thereby altering structural demand [10, 11, 2]. Zhou et al. [12], in their work, a new uplift foundation analysis model to simulate dynamic nonlinear soil-structure-interaction showed that if uplift occurs, the response of super-structure decreases.

Meanwhile, the response of the foundation shows an upward trend, which can imply that the super-structure's response could be declined due to the uplift occurring between the foundation and the soil. Psycharis [13], in his work dynamic behavior of rocking structures allowed to uplift, stated that the apparent resonant fundamental frequency of uplifting systems is always less than the resonant fundamental frequency of an interacting system in which uplift is not allowed as uplift leads to softer vibrating systems. He also stated that from the engineering point of view, one is normally more interested in the rocking response rather than the vertical response. But for many potential applications, vertical response is important for excitations that can result in uplift.

Most of these works on foundation uplift were based on the one-parameter elastic foundation model (Winkler model). The Winkler model has been used extensively for soil-structure interaction problems and has given satisfactory results with its own shortcomings and deficiencies, as there is no continuity between the loaded and unloaded part of the foundation surface. This study tends to analyze the vulnerability of structures on elastic foundations considering soil flexibility on the two-parameter foundation model, which is an improvement on the shortcomings of the one-parameter model. The influence of soil flexibility during uplifting, considering a two-parameter elastic foundation, will be compared with the Winkler foundation model.

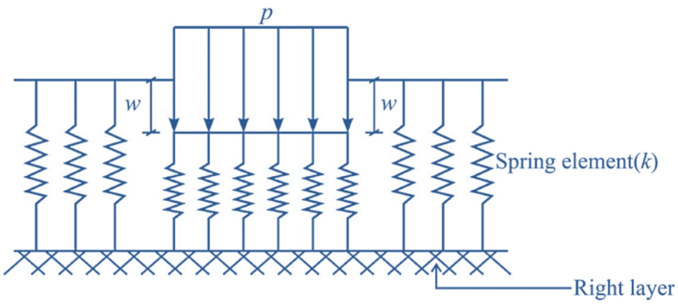

**Fig. 1 Winkler One-Parameter foundation model**

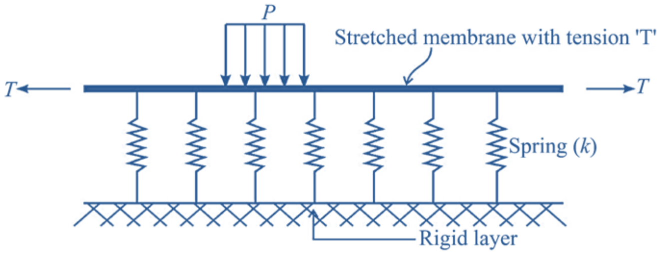

**Fig. 2 (F-B) foundation model**

### 1.1. Elastic Foundation Model

All structural loads are transferred to the soil, and both structure and soil continuum act together to support the loads. There is a need to develop more realistic foundation models and simplified methods to solve this complex soil-structure interaction problem for safe and economical designs. The elastic modeling of the soil is based on the assumption of the behavior of sub-grade reaction under loading. The dynamic behavior of structures on elastic foundations has been investigated by many researchers in engineering Hamarat et al., [14] to predict the behavior and response of structures from the dynamic source. These studies mostly considered the Winkler foundation (one-parameter foundation model) of Figure 1 because of its simplicity and satisfactory results for many practical problems. However, due to the shortcomings of one one-parameter foundation model, it gave rise to the development of various forms of two-parameter models, three-parameter models, continuum models, and mixed models used to improve on and make more realistic the classical Winkler model [15, 16, 17]. In this study, the elastic foundation of Filonenko-Borodich (F-B) of Figure 2 foundation models is to be considered for flexibility effect on response analysis.

The Winkler model is based on the pure bending beam theory and assumes a linear load versus settlement relation; that is, the deflection at each point is proportional to the pressure applied to that point, and there is complete independence of deflections occurring at the neighboring parts along the foundation [18]. The deformations outside the loaded area were neglected and taken as zero.

$$P(x) = kw \qquad (1)$$

Where:
$w$ = vertical translations of the soil produced by applied load,
$P$ = contact pressure,
$k$ = modulus of the foundation.

According to the F-B model, it requires continuity between the individual spring elements in Winkler's model by connecting the top ends of the springs to an elastic membrane stretched to a constant tension 'T' [16].

$$P(x) = kw - T\frac{d^2w}{dx^2} \qquad (2)$$

## 2. Methodology

### *2.1. The Model Systems*

The systems are buildings with height 'H' and width' 2B', as seen in Figure 3 and Figure 4 on Winkler and F-B foundations. Each has a concentrated mass' m' from ‘W = $m_g$’ at the centre, and gravity is assumed to point downwards. ‘W’ is weight, and ‘g’ is acceleration due to gravity. The model systems are assumed to have homogeneous and linear properties connected to a rigid base and elastic foundation. It is of height ‘h’ above the foundation supported on the soil, and the body cannot slip between the foundation and supporting elements. From this assumption, the body has two degrees of freedom: vertical motion measured from the position of rest by vertical displacement and rotation measured by the angle of tilting ‘α’ from the vertical. The body is assumed not bonded to soil elements. It is resting on soil spring elements only through gravity and because of poor performance of soil in carrying tensile stresses leading to foundation uplift.

Thus, the supporting soil elements can provide an upward force to the foundation, not a downward pull. During ground motion, this upward reaction force will vary with time, and anytime when one edge of the foundation gets to the natural unstressed level of the spring elements, that edge is in a state of undergoing uplift. As upward displacement continues, some foundation parts uplift from supporting elements. Considering uplift, two contact conditions are given: when the structure base is in full contact with supporting soil and when there is partial separation (uplift) of the structure base from supporting soil elements.

The Winkler foundation of Figure 3 assumes that deflection at each point is proportional to the pressure applied to that point. Deflections outside the loaded area are neglected and taken to be zero. The elastic zone is connected to the base, which is assumed to be rigid, and the stiffness of the soil spring is ‘$k_w$’. The Winkler’s foundation model is a crude approximation of the correct mechanical behaviour of the soil media as it disregards the effect of continuity and cohesion of the ground, hence the two-parameter model. Filonenko-Borodich of Figure 4 improved on the Winkler model by connecting the top ends of the spring elements to a smooth, thin elastic membrane stretched to a constant ‘T’ for continuity, as it tends to provide more reliable information on stresses and deformations of the soil media. It has two foundation parameters, spring constant ‘$K_f$’ and applied tension ‘$T$’.

### *2.2. Foundation Flexibility on the System Response*

In the determination of system response, equations of motions were derived for the Winkler and F-B foundation models. The system is assumed to undergo small displacements and consists of a sequence of linear problems with degrees of freedom. Firstly, vertical motion is measured from the position of rest by vertical displacement ‘$y$’ at the centre of mass and secondly, the rotation is measured by the angle of tilting ‘α’ from the vertical with inertia forces; $-m\ddot{a}_{Gy}$ and $-ma_{Gx}$ applied at the centre of mass of the structure. ‘V’ is the effect of the foundation continuity. $P_{kw}$ and $P_{kf}$ are spring element forces of the Winkler and F-B model. The horizontal direction was ignored because frictional forces along the structure surface in contact with the foundation are assumed high enough to prevent sliding. Two foundation conditions, namely foundation on full contact with the supporting spring elements and foundation with uplift, were analyzed. For each condition, equations of motion were derived for the system’s vertical ‘y’ and rocking direction ‘x’. The equations were derived using Newton’s second law of motion, applying D’Alembert’s principle, considering the moment equilibrium of forces on the system. The equations of motion of the foundation models are now solved using the Simpson method for the system responses.

### *2.3. Before Uplift*

In this condition, the equations of motion are linear for small displacements and are governed by the standard classical theory of soil structure interaction and differential equations for a single degree of freedom system [8].

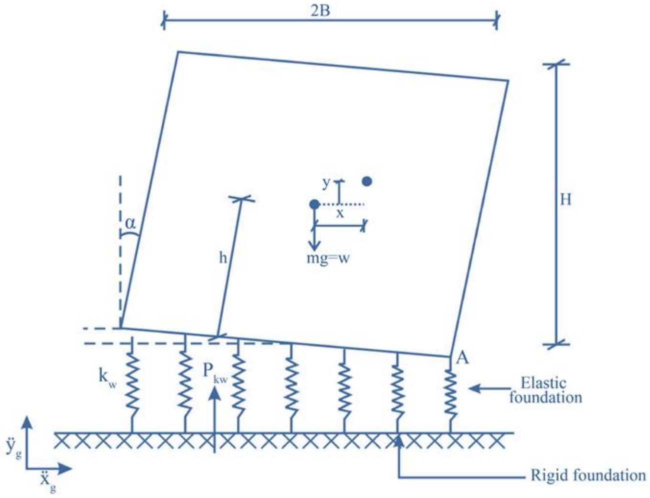

**Fig. 3 A structure on one-parameter foundation model**

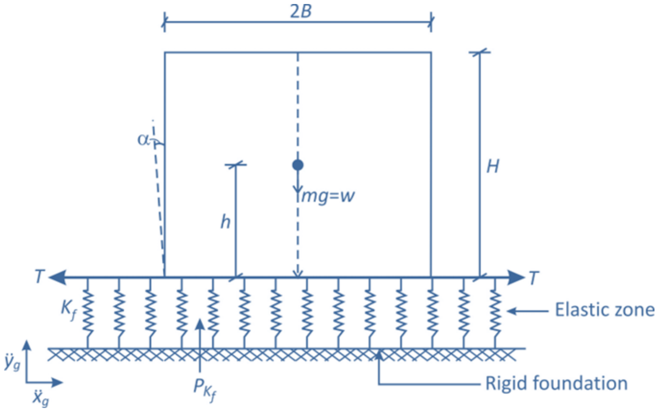

**Fig. 4 Structure on Two-Parameter foundation (F-B model)**

### 2.3.1. Vertical Direction

Using Newton's second law of motion and considering the equilibrium of forces

$$\sum f_y = 0 \quad (3)$$

$$Pk_w - W - m\mathrm{a}_{Gy} = m\ddot{y} \quad (4)$$

But,

$$Pk_w = W - 2k_wBy \quad (5)$$

Using Equation (5) and Equation (4) gives;

$$m\ddot{y} + 2k_wBy = -m\mathrm{a}_{Gy} \quad (6)$$

### 2.3.2. Rocking Direction

Considering the equilibrium of moments about the base centre 'C':

$$\sum M_C = 0$$

$$m = Wh\alpha - (2k_wBy)h\alpha - \frac{1}{12}k_w(2B)^3\alpha + R_A[h + B\alpha] \quad (7)$$

$$m = [W \times h\alpha] - [2k_wBy \times h\alpha] + R_A[h + B\alpha] - \frac{8k_wB^3}{12}\alpha = 0 \quad (8)$$

But $R_A$ is the restraining force preventing the structure from sliding horizontally at point A

$$R_A = -m\ddot{x}_G - m\ddot{x} = m\ddot{x}_G - mh\ddot{\alpha} \quad (9)$$

Applying Equation (9) into (8)

$$Wh\alpha - 2k_wByh\alpha - m\mathrm{a}_{Gx}h - mh^2\ddot{\alpha} - m\mathrm{a}_{Gx}B\alpha - mBh\ddot{\alpha}\alpha - \frac{8k_wB^3}{12}\alpha = 0 \quad (10)$$

Therefore,

$$I_c\ddot{\alpha} + mBh\alpha\ddot{\alpha} - Wh\alpha + 2k_wByh\alpha + m\mathrm{a}_{Gx}B\alpha + \frac{2}{3}k_wB^3\alpha = -mh\mathrm{a}_{Gx} \quad (11)$$

Equations (6) and (11) are equations of motions for Winkler's foundation on full contact.

In like manner, the equations of motion for F-B foundation on full contact;

For the vertical direction;

$$m\ddot{y} + 2k_fVy = -m\ddot{a}_{Gy} \quad (12)$$

For the rocking direction;

$$2I_c\ddot{\alpha} + \frac{2k_fV^3\alpha}{3} = -2mha_G \quad (13)$$

The width of the F-B foundation is 2V, which is the length of the stretched tension applied continuity effect.

### 2.4. During uplift

Then, equations of motion are highly nonlinear because of varying degrees of contact between structure and foundation as the system continuously changes from one linear state to another. The governing equations can be derived by considering the lateral equilibrium of forces acting on the structure and the moment equilibrium of forces on the system.

### 2.4.1. Vertical Direction

Using Newton's second law of motion and summing forces,

From Equation (5),

$$Pk_w = W - \frac{1}{2}k_wFq \quad (14)$$

Where F = length of contact during uplift
q = depth of uplift.

The Winkler's spring constant '$k_w$', considering the length of foundation contact

Substitute Equation (14) into Equation (4):

$$W - \frac{1}{2}k_wFq - W - m\mathrm{a}_{Gy} = m\ddot{y} \quad (15)$$

Rearranging Equation (15) becomes;

$$m\ddot{y} - \frac{1}{2}k_wFq = -m\mathrm{a}_{Gy} \quad (16)$$

From Equation (16), because of uplift, the equation of motion is highly nonlinear because of varying degrees of contact 'F' and 'q' between structure and foundation as the system continuously changes from one linear state to another. By linearising the equations gives vertical direction on Winkler foundation as;

$$\ddot{y} - \frac{k_w}{2m}B^2\alpha + \frac{k_wBy}{\mathrm{m}} = -\mathrm{a}_{Gy} - \frac{W}{2m} \quad (17)$$

### 2.4.2. Rocking Direction

Considering the equilibrium of moments about the centre of the structure base,

$$m = Wh\alpha - \frac{k_w}{12}(2B)^3\alpha - \left(2\frac{k_w}{2}By\right)h\alpha - \frac{k_w}{2}\left(Fq \times \frac{F}{3}\right)h\alpha + R_A(h + B\alpha) \quad (18)$$

Expanding Equation (18) and using (9) then ignoring nonlinear terms:

Where 'I' = moment of inertia about center of base point 'c'.

$$I_c = mr^2 = mh^2 \quad (19)$$

Therefore;

$$I_c\ddot{\alpha} + \frac{2}{3}k_w B^3\alpha + \frac{W^2h}{8k_wB} - \frac{Why}{2} = -mha_{Gx} \tag{20}$$

This is the equation for the rocking direction on the Winkler foundation.

Using the same procedure, the F-B equations during uplift become;

For the vertical direction;

$$\ddot{y} + \frac{k_fV}{m}\left[y - \frac{V\alpha}{2}\right] = -a_{Gy} - \frac{W}{2m} \tag{21}$$

For the rocking direction;

$$2I_c\ddot{\alpha} + \frac{2k_fV^3\alpha}{3} + \frac{w^2h}{8k_fV} - \frac{why}{2} = -2mh\ddot{a}_G \tag{22}$$

### *2.5. Solution of Equations of Motions*

#### *2.5.1. Before Uplift*

In solving the equations of motion, some assumptions were applied to simplify solving the equations of motion as the structure is assumed to undergo small displacements. The Duhamel integral was applied for the system response, and this response is in the neighborhood of equilibrium points. On full contact, the system at rest condition assumes that $x_0 = \dot{x}_0 = 0$, the input acceleration is $\ddot{a}_G$ with 'y' and 'x' components.

Winkler foundation from Equation (6) and (11) becomes

$$y(t) = -\frac{1}{\omega_3}\int_0^t a_{Gy}(\tau)\sin\omega_3(t-\tau)d\tau \tag{23}$$

$$x(t) = -\frac{mh^2}{I_c\omega_4}\int_0^t a_{Gx}(\tau)\sin\omega_4(t-\tau)d\tau \tag{24}$$

F-B foundation: from Equations (12) and (13) gives;

$$y(t) = -\frac{1}{\omega_7}\int_0^t \ddot{a}_{Gy}(\tau)\sin\omega_7(t-\tau)d\tau \tag{25}$$

$$x(t) = -\frac{1}{\omega_8}\int_0^t \frac{mh^2a_{Gx}}{I_c}(\tau)\sin\omega_8(t-\tau)d\tau \tag{26}$$

#### *2.5.2. During Uplift*

The system condition is that the initial time uplift will start when the system deflection equals the vertical displacement. Then;

Winkler's model from Equations (17) and (20) for vertical and rocking direction;

$$y(t) = y(0)\cos\omega_{3A}t + \frac{\dot{y}(0)}{\omega_{3A}}\sin\omega_{3A}t - \frac{1}{\omega_{3A}}\int_0^t \left[a_{Gy} + \frac{W}{2m}\right](\tau)\sin\omega_{3A}(t-\tau)d\tau \tag{27}$$

$$x(t) = x(0)\cos\omega_{5u}t + \frac{\dot{x}(0)}{\omega_{5u}}\sin\omega_{5u}t - \frac{1}{I_c\omega_{5u}}\int_0^t \left[mh^2a_{Gx} + \frac{W^2h^2}{8k_wB}\right](\tau)\sin\omega_{5u}(t-\tau)d\tau \tag{28}$$

F-B foundation from Equations (21) and (22) for the vertical and rocking direction;

$$y(t) = y(0)\cos\omega_{7A}t + \frac{\dot{y}(0)}{\omega_{7A}}\sin\omega_{7A}t - \frac{1}{\omega_{7A}}\int_0^t \left[a_{Gy} + \frac{W}{2m}\right](\tau)\sin\omega_{7A}(t-\tau)d\tau \tag{29}$$

$$x(t) = x(0)\cos\omega_8t + \frac{\dot{x}(0)}{\omega_8}\sin\omega_8t - \frac{1}{I_c\omega_8}\int_0^t \left[mh^2a_{Gx} + \frac{W^2h^2}{16k_fV}\right](\tau)\sin\omega_8(t-\tau)d\tau \tag{30}$$

The system responses were solved using Simpson's numerical method.

## 3. Results

The forcing function is 0.32G taken as the seismographic record of the El-Centro earthquake ground acceleration data of 1940 used as the maximum ground acceleration with impulse (Figure 5), and 'G' is the acceleration of gravity in m/s$^2$. The structure is an industrial building of dimension 26m x 14m and 7.5m high above the ground level with a mass assumed to be 4078kg and the mass located at height 'h' = 3.2m from ground level.

The spring stiffness is 1.8x10$^6$N/m$^3$. The moment of inertia about the center of the base is 2.6x10$^4$ m$^4$. The natural frequency and period of the system were evaluated, which were employed in the analysis using Simpson's numerical method for the responses. From the analysis, the system response with regard to the natural frequency, period, displacements, and 0velocities for the Winkler and F-B foundations are presented below.

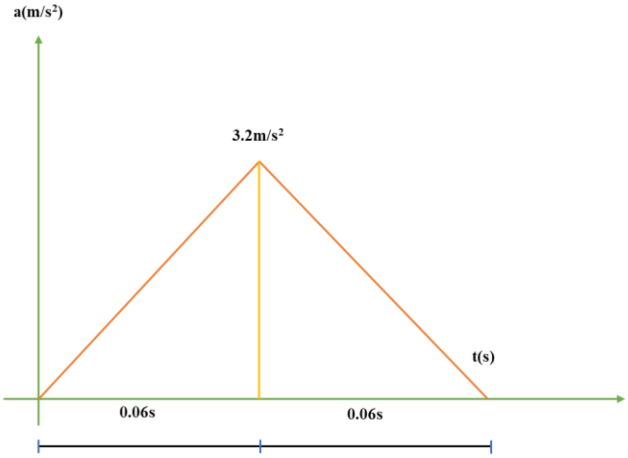

**Fig. 5 Triangular impulse loading history of the earthquake ground motion**

**Table 1. Fundamental natural frequency (rad/s)**

| S/No | Model Type | Before Uplift | | During Uplift | |
|---|---|---|---|---|---|
| | | Vertical | Rocking | Vertical | Rocking |
| 1 | Winkler Model | 33.10 | 52.88 | 16.552 | 43.872 |
| 2 | (F-B) Model | 36.47 | 50.13 | 18.24 | 53.27 |

**Table 2. Natural periods (secs.)**

| S/No | Model Type | Before Uplift | | During Uplift | |
|---|---|---|---|---|---|
| | | Vertical | Rocking | Vertical | Rocking |
| 1 | Winkler Model | 0.03 | 0.019 | 0.0604 | 0.0228 |
| 2 | (F-B) Model | 0.027 | 0.02 | 0.0548 | 0.0187 |

Table 1 shows the fundamental natural frequency of the system for the vertical and rocking components for the Winkler model, and the F-B model before uplift is greater than during uplift. This reduction of natural frequency during uplift might result from increased system flexibility. Comparing the vertical and rocking frequencies showed that frequencies in the rocking directions are bigger and, as a result, are stiffer when compared to the vertical direction. This flexibility of the system helps to reduce energy going into the structure, though the ductility of the soil structure interaction is reduced. The F-B model showed the same trend as Winkler's but gave an increased natural frequency during uplift in the rocking direction, which can be from the effects of soil spring continuity on the structure.

- The natural periods of oscillation of Table 2 showed the structure of the Winkler model increased with the occurrence of uplift for the vertical and rocking components. This can be from the reduction in the soil stiffness, which then causes an increase in the natural period of oscillation when uplift occurs, depending on the frequency content of the ground motion. This elongation of the natural period is very significant as it can alter the seismic response of the system; hence, foundation uplift is important when analyzing short-period structures, as the natural period of the soil is sensitive to foundation flexibility. The periods in rocking components decreased compared to the vertical component in the F-B model.
- The rocking component of the F-B model during uplift showed a decreased period, which can be attributed to the continuity interactions of the spring elements from Table 2.

Tables 1 and 2 above showed that the rocking natural frequency increased more than the vertical natural frequency when the natural periods of oscillation were reduced for the case of before and after uplift. That is, natural frequency increases in the rocking direction at reduced rocking periods because as the flexibility of the structure increases, the period of oscillation or time taken to undergo a complete cycle is reduced or shortened. As well, the ductility of the soil structure system is reduced. But, considering the uplift effect, the reduction of the contact area between the soil and foundation brought about an increase in support flexibility, thereby leading to reduced soil-structure stiffness. This may increase in the natural period of oscillation. So, during uplift, there is elongation of the period of oscillation as the foundation becomes softer. This is in line with Psycharis [13] that the resonant fundamental frequency of uplifting systems is always less than the resonant fundamental frequency of an interacting system in which uplift is not allowed as uplift leads to softer vibrating systems.

- The vertical displacements are rather very important when foundation uplift becomes pronounced as uplift can induce significant vertical displacement on the structural response because, at this stage, the static deflection of the structure can be affected, thereby being exceeded. The result showed that the relative decrease in vertical displacement with respect to static deflection brought about an increase in the rocking aspect. Hence, accurate calculation in the vertical direction is important for analyzing uplift problems since uplift occurrence depends on its vertical displacement before uplift during seismic loading. The displacement effects showed the F-B foundation in a better representation than the Winkler model before uplift, as in Figures 5 and 6, respectively. It showed the crude approximations nature of the Winkler model that disregarded the effect of continuity and cohesion of the ground. Hence, the two-parameter model proposed by F-B improves the Winkler and gives a better response.

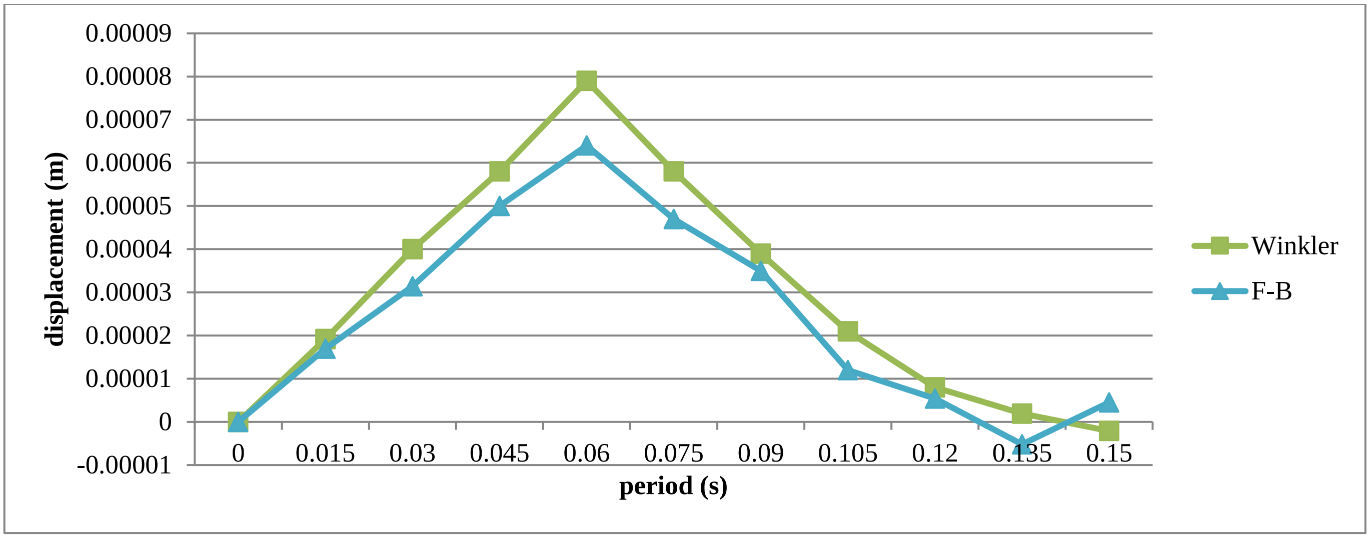

**Fig. 5 Vertical displacement of each model before uplift**

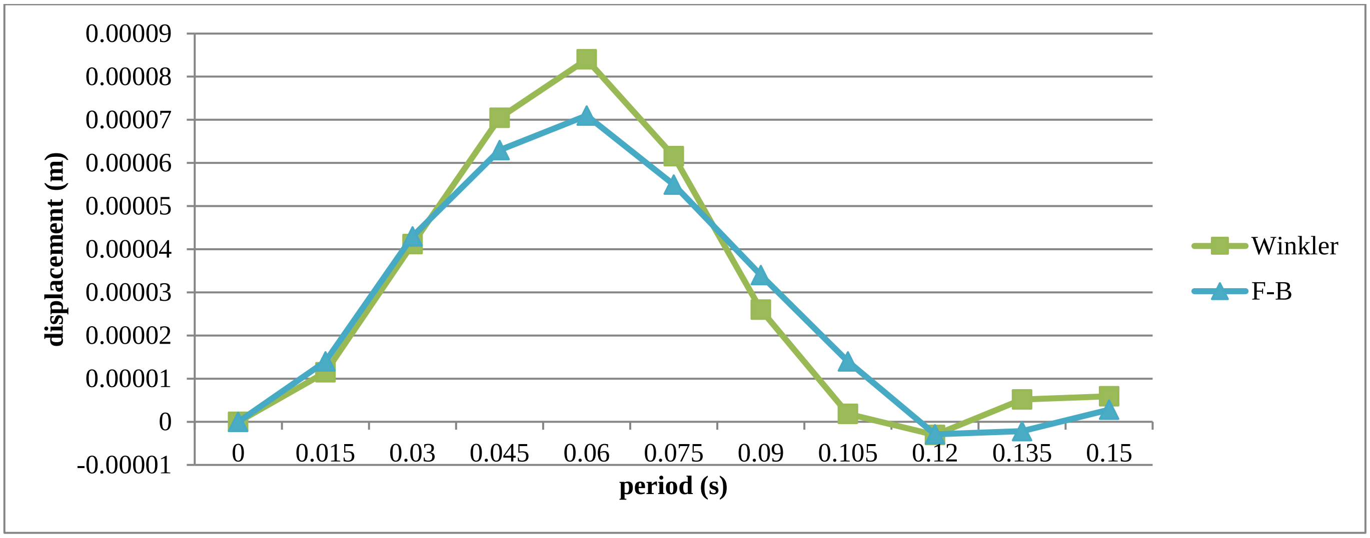

**Fig. 6 Rocking displacement of each model before uplift**

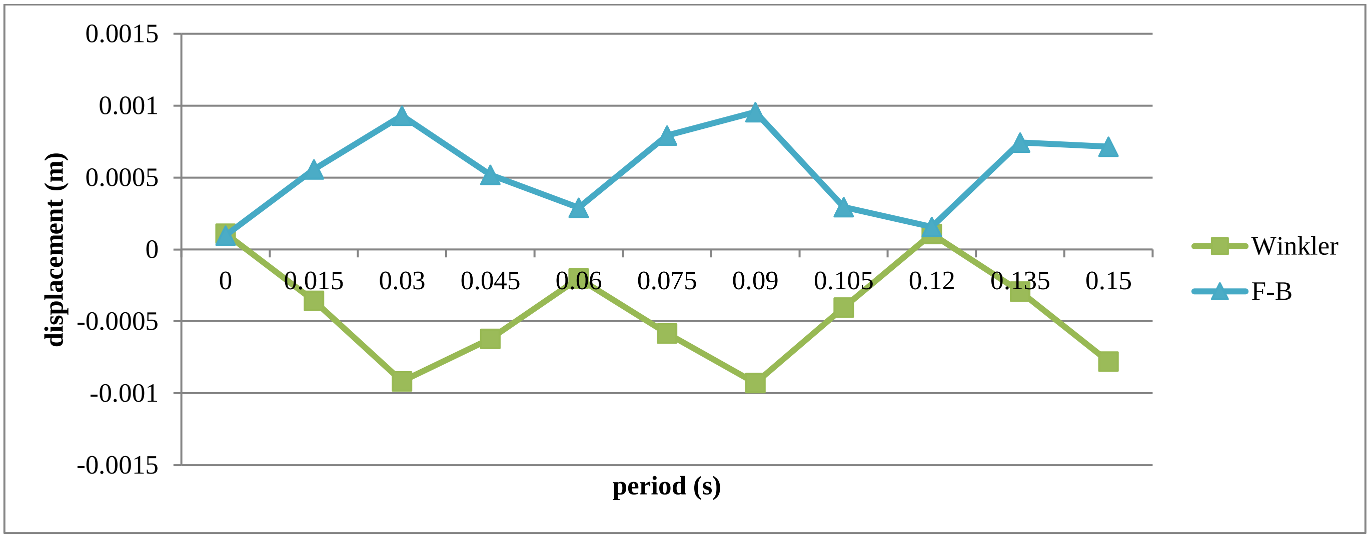

**Fig. 7 Vertical displacement of each model during uplift**

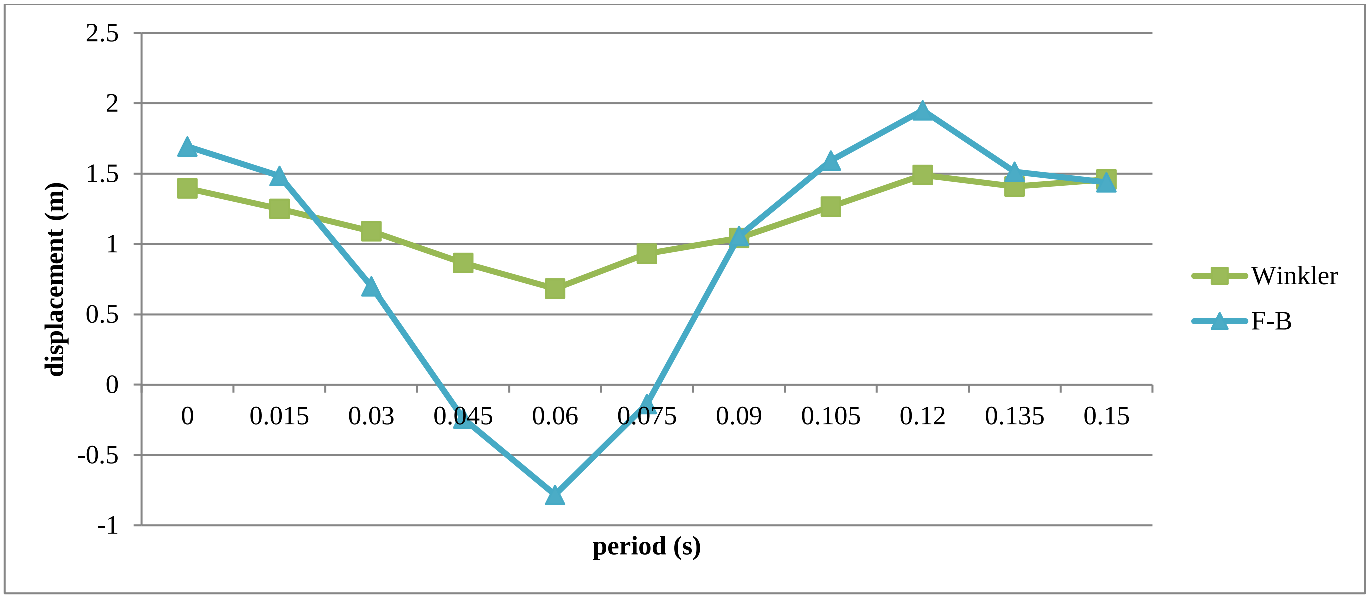

**Fig. 8 Rocking displacement of each model during uplift**

During uplift, Figures 7 and 8 showed the F-B foundation model continuity effects on the system response, showing the significant nonlinear nature of the system with the F-B model.

- Earthquake engineering gives the necessary tools to limit structure damage by designing structures for high earthquake resistance. Duhamel integral was used to determine the response of a time-dependent system induced by an external force, which includes displacement, velocity, natural frequency, and period of the system. If the displacement and velocity of the system are known at some time, the state of the system at subsequent times can be computed with the response spectra plotted against time. This is shown in Figure 5 to Figure 12.
- From the displacement curve of the vertical and rocking direction when the foundation is in full contact, shown in Figure 5 and Figure 6, the Winkler model was more prominent than the F-B model, which can be due to some estimation associated with the supporting system of Winkler resulting to high displacement values. However, the two supporting systems have a better representation of the actual condition of a continuous series of spring elements and their curve shapes are better represented. The tension field of the F-B model has the physical effect of reducing the foundation reaction pressure [16].

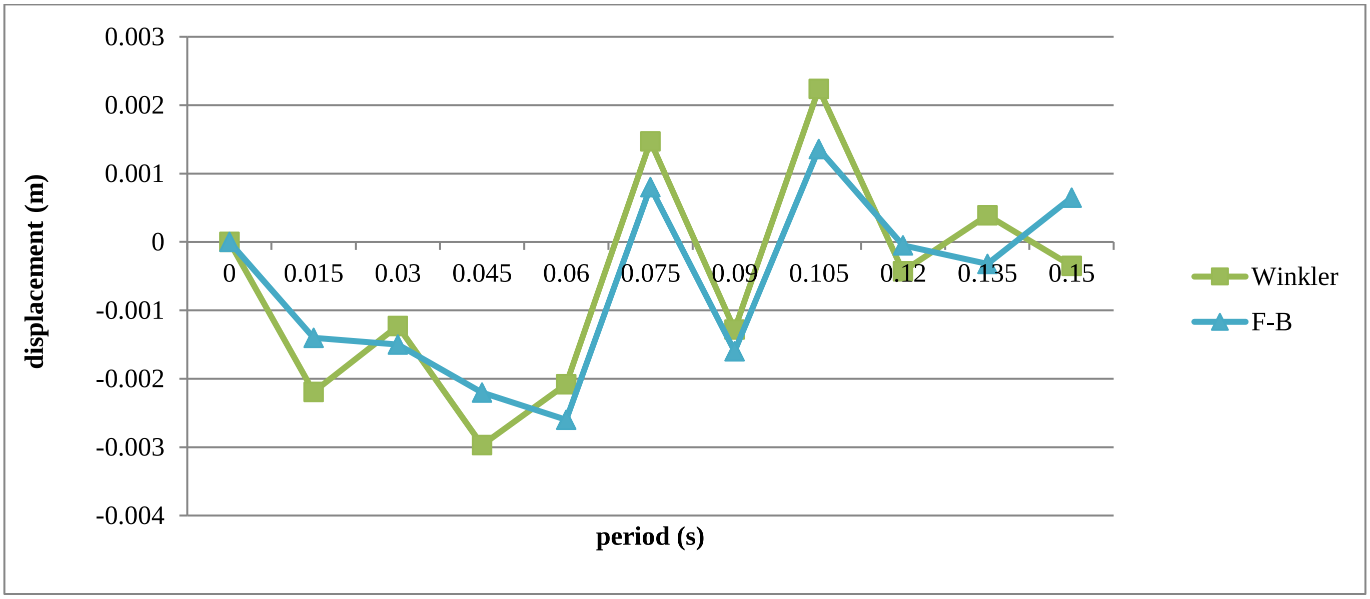

**Fig. 9 Vertical velocity of each model before uplift**

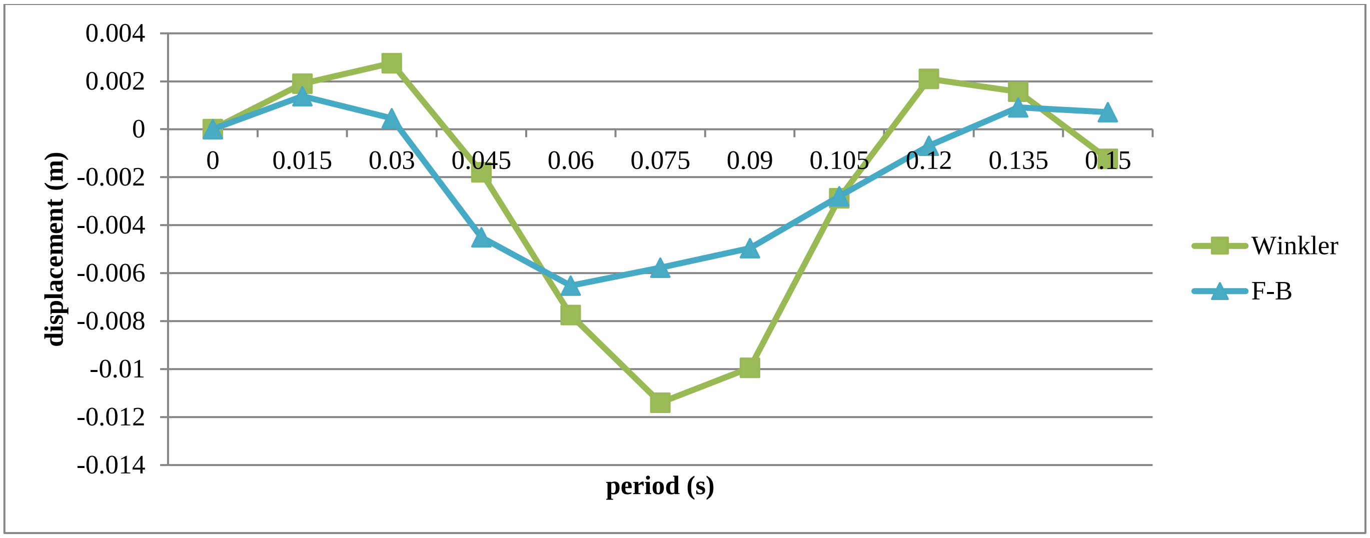

Fig. 10 Rocking velocity of each model before uplift

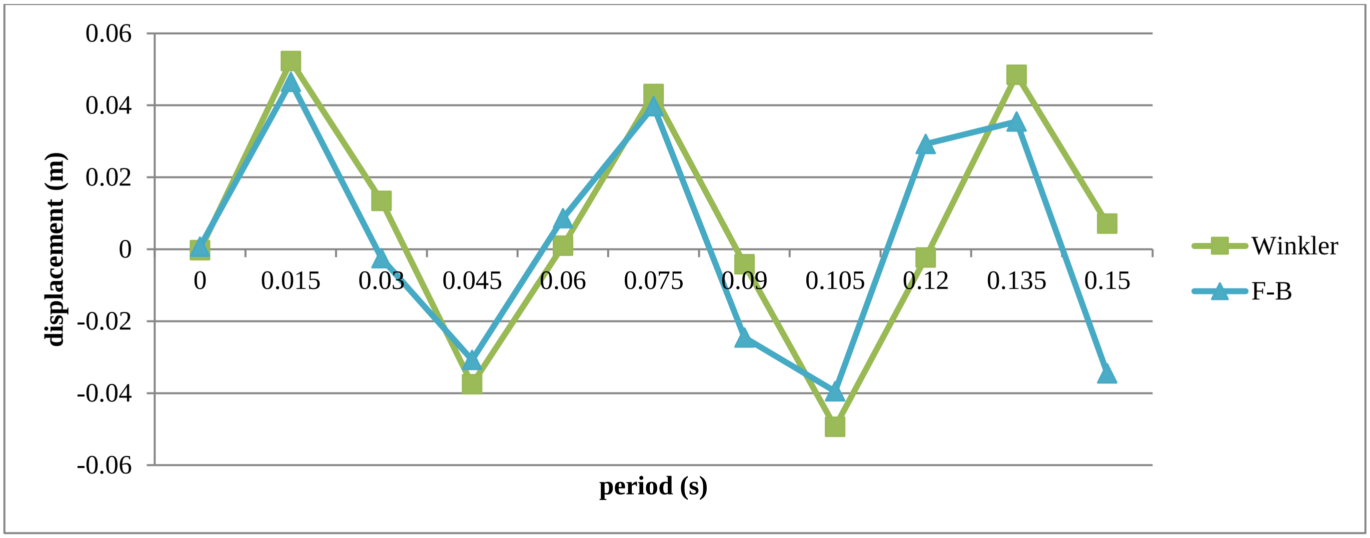

Fig. 11 Vertical velocity of each model during uplift

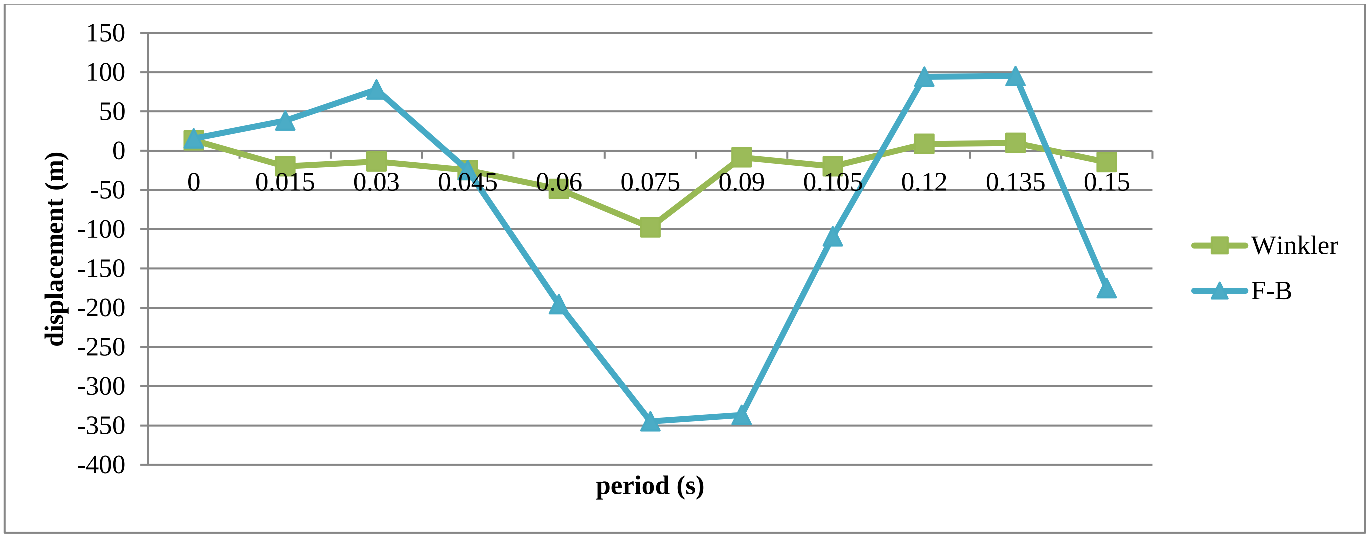

Fig. 12 Rocking velocity of each model during uplift

- The sensitivity of the rocking response of the system is obvious from the applied ground motion. This can be seen from the case of before uplift and during uplift as the displacement and velocity values of the system increase as compared to the system's vertical responses. The system rocking response showed sensitivity to small changes to the details of ground motion and system parameters. During uplift, the system response increased for the foundation models as uplifting of the system led to an increase in the system response for both foundations.
- It is evident from the results gotten that responses from the rocking directions are more significant than the vertical responses during uplift, which, from the engineering point of view, attention should be given to the rocking response as the vertical response that causes uplift reduces the possibility of complete separation of the structure base and foundation.

## 4. Conclusion

In the interaction of the soil and structure, there is a reduction of the system's fundamental frequency for the Winkler foundation. This reduction during uplift resulted in increased flexibility of the system, and this flexibility reduces the ductile nature of the soil system. This can be attributed to Zhou et al. [12]; in their work, a new uplift foundation analysis model to simulate dynamic nonlinear soil-structure-interaction showed that if uplift occurs, the response of super-structure decreases and the response of the foundation shows an upward trend which can impute that the response of the super-structure could be declined due to the uplift occurring between the foundation and the soil. The rocking frequencies are greater and stiffer than vertical frequencies. The system's flexibility helped reduce energy inflow into the structure, thereby reducing the resonance phenomenon. F-B foundation tends to have an increased natural frequency during uplift, which might be from the spring continuity effects on the structure. In the case of strong ground motion that can cause uplift, the structure becomes softer, and the fundamental frequency is reduced. Since the structure is in a nonlinear state resulting from uplifting, this frequency depends on the excitation and decreases as the amplitude of the excitation increases. Determining the natural frequency in a system is the foremost and fundamental principle in the dynamic analysis and design of structures. The structure's response during uplift may differ from the response before uplift, which might depend on the parameters of the structure foundation and intensity of excitation, which then determine if structure uplift is beneficial or not. The natural periods of oscillation of the structure for the foundation models increased with the occurrence of uplift coming from a reduction in the soil stiffness depending on the frequency content of the ground motion. This elongation of the natural period is very significant as foundation uplift is important when analyzing short-period structures, as the natural period of the soil is sensitive to the foundation's flexibility and ductility. But, considering the uplift effect on the structure, the reduction of the contact area between the soil and foundation brings about an increase in support flexibility, thereby leading to reduced soil-structure stiffness. This may result in an increase in the natural period so that during uplift, the period increases as the foundation becomes softer. The analysis showed that during system uplift, the system response increased for the foundation models, leading to increased system responses for the vertical and rocking directions. It is evident from the results that responses from the rocking directions are much more significant than the vertical responses. Hence, from the engineering point of view, one is very interested in the system's rocking response as the vertical response for uplifting systems for the structure's integrity.

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