CRITICAL RESPONSE OF NONLINEAR BASE-ISOLATED BUILDING CONSIDERING SOIL-STRUCTURE INTERACTION

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Abstract

The critical nonlinear response considering soil-structure interaction is investigated for a base-isolated building under a multi impulse as a representative for long-duration ground motions. Recently, Luco [1] presented a numerical result on the nonlinear steady-state response of a base-isolated building with nonlinear isolators on flexible ground by using the equivalent linearization technique [2], which requires the repetition in the determination of equivalent parameters and the sweeping with respect to excitation frequency. On the other hand, it is shown here that an explicit solution can be derived for the elastic-plastic response of a single-degree-of-freedom (SDOF) system by using a multi impulse as an input. It enables the analytical clarification of the mechanism of soil-structure interaction effect. It is also clarified that, while the decrease of ground stiffness increases the maximum deformation of the base-isolation story under the condition of constant acceleration amplitude of the input, the ground stiffness does not influence the maximum deformation so much under the condition of constant velocity amplitude of the input.

The present paper is based on the research by Kojima and Takewaki [3] which introduced the multi impulse as a substitute for a multi-cycle sine wave. Since only the free vibration appears under the impulse input, an approach based on the energy balance law enables the simple expression of complex elastic-plastic response. Although the resonant sinusoidal frequency should be analyzed for a specified input level by changing the input frequency parametrically in general [4, 5], the critical resonant frequency can be found automatically for the gradually increasing input level when using the multi impulse. The maximum Fourier amplitude of the multi impulse is set so as to be equal to that of the corresponding multi-cycle sine wave. The complicated model of the nonlinear base-isolated building considering soil-structure interaction is first modeled into a 2DOF system (SDOF superstructure and base-isolation story) on a swaying-rocking spring-dashpot system. Then that system is transformed into a SDOF system on a swaying-rocking spring-dashpot system by neglecting the mass on the base-isolation story. Finally, the reduced system is further transformed into a SDOF system by neglecting the mass and moment of inertia of the base mat. Since an explicit expression had been derived in the previous paper [6] on the maximum elastic-plastic response of a damped bilinear hysteretic SDOF system subjected to the "critical multi impulse input" causing the maximum response for variable interval of impulses with the constant input velocity level, this expression is applied to the finally transformed SDOF system. Once the maximum deformation of the equivalent SDOF system is obtained, the corresponding maximum deformation of the base-isolation story can be derived by subtracting the remaining deformations from the total deformation. The accuracy and reliability of the proposed method are demonstrated by using the time-history response analysis for the corresponding original multi-degree-of-freedom (MDOF) model under a multi impulse and comparing with the result by Luco [1].

Keywords: base isolation; soil-structure interaction; critical nonlinear response; multi impulse; long-duration ground motion.

1. Introduction

Base-isolated buildings are preferred in general to be constructed on hard ground because the main purpose of base-isolation is to cut off the short-period components of earthquake ground motions. Nevertheless, base-isolated buildings have been constructed even on soft ground these days, which may induce long-period earthquake ground motion components. Actually, there are some examples for the case that the long-period component of earthquake ground motions causes vibration resonance to high-rise buildings located far from the epicenter [7]. Once the resonance occurs in base-isolated buildings on softer ground, the influence of soil-structure interaction on the response of base-isolated buildings may be significant. From these points of view, the effects of soil-structure interaction on base-isolated buildings should be investigated in detail.

The effects of soil-structure interaction on base-isolated building have been investigated by several researchers, and they showed that the ground stiffness significantly affects the responses of base-isolation story and the superstructure [8-10]. Especially, Luco [1] presented a numerical result on nonlinear steady-state response for a base-isolated building with nonlinear isolators on flexible ground by using the equivalent linearization technique [1, 2].

Nonlinear steady-state response analysis requires the repetition in the determination of equivalent parameters and the sweeping with respect to excitation frequency [4, 5]. On the other hands, Kojima and Takewaki [3] proposed to use a 'multi impulse' as a representative for long-duration ground motions for avoiding such repetition. This innovative approach is based on the energy balance law and enables the simple analytical expression of complex elastic-plastic response [11].

Subsequently, Akehashi et al. [12] investigated the critical nonlinear response of a base-isolated building system considering soil-structure interaction under near-fault earthquake ground motions by using a double impulse. However, the critical nonlinear response considering soil-structure interaction has never been investigated for a base-isolated building under a multi impulse. In general, the effect of soil-structure interaction under long-duration ground motions is much larger than that under short-duration ground motions like a pulse wave. Therefore, it is important to clarify such effect under long-duration ground motions.

In this paper, a complicated model of a nonlinear base-isolated building considering soil-structure interaction is first modeled into a 2DOF system (SDOF superstructure and base-isolation story) on a swaying-rocking spring-dashpot system. That model is transformed into a SDOF model through a two-stage procedure. Since an explicit expression had been derived in the previous paper on the maximum elastic-plastic response of a damped bilinear hysteretic SDOF system subjected to the "critical multi impulse input" causing the maximum response for variable interval of impulses with the constant input velocity level [6], this expression is applied to the finally transformed SDOF system. It leads to the analytical clarification of the mechanism of soil-structure interaction effect.

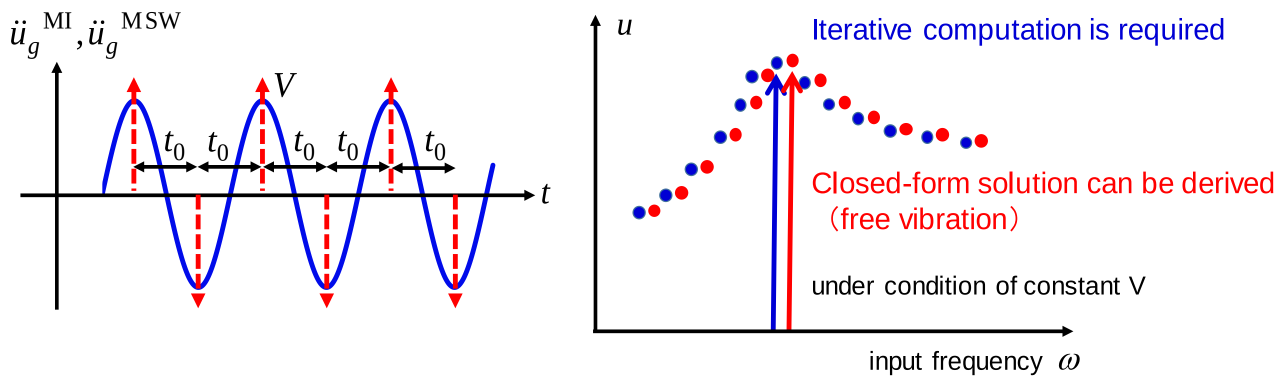
2. Multi impulse

The ground acceleration of a multi impulse and the corresponding multi-cycle sine wave are expressed as follows (Fig. 1(a)).

$$\ddot{u}_g^{\mathrm{MI}} = \sum_{n=1}^{N} (-1)^{n-1} V \delta\{t-(n-1)t_0\} \tag{1}$$

$$\ddot{u}_g^{\mathrm{MSW}} = A_l \sin(\pi t / t_0) \quad (0 \le t \le N t_0), \tag{2}$$

where $V, t_0, N, \delta(t), A_l$ are the input velocity, the time interval and the number of multi impulses, the Dirac delta function, and the acceleration amplitude of the corresponding multi-cycle sine wave, respectively. The Fourier amplitudes of $\ddot{u}_g^{\mathrm{MI}}$ and $\ddot{u}_g^{\mathrm{MSW}}$ can be derived as follows.



(a) (b)

Fig. 1 – Comparison of multi impulse and corresponding multi-cycle sine wave, (a) ground acceleration, (b) resonance curve for constant velocity amplitude with and without repetitive computation

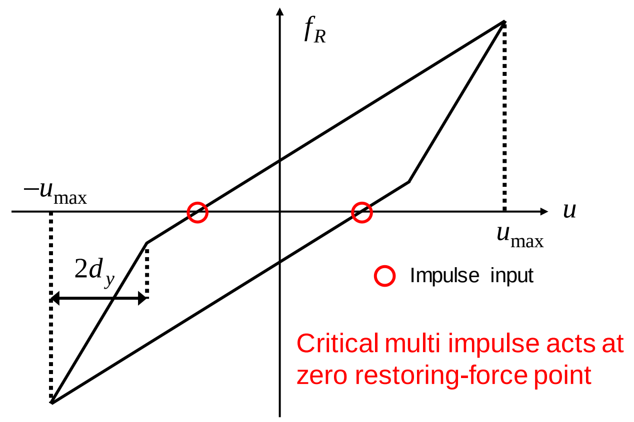
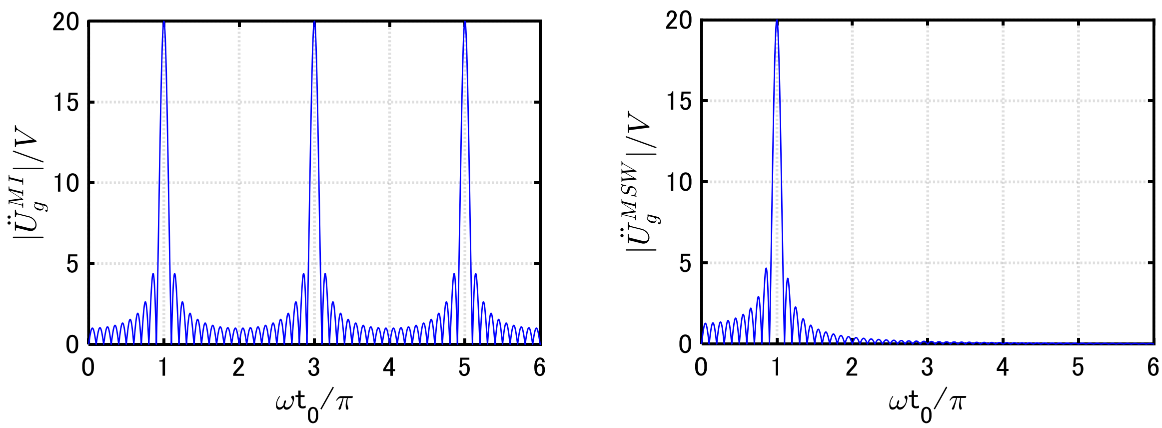


Fig. 2 – Restoring force-deformation relation under multi impulse and critical impulse timing defined by zero restoring force



(a) (b)

Fig. 3 – Fourier amplitude, (a) multi impulse, (b) corresponding multi-cycle sine wave

$$\left|\ddot{U}_g^{\mathrm{MI}}\right| = V\left|\sum_{n=0}^{N-1}(-1)^n e^{-i\omega n t_0}\right| \tag{3}$$

$$\left|\ddot{U}_g^{\mathrm{MSW}}\right| = \left|\int_{-\infty}^{\infty} \ddot{u}_g^{\mathrm{MSW}} e^{-i\omega t}\, dt\right| = \left|\frac{\pi A_l t_0}{\pi^2 - (\omega t_0)^2}(1 - e^{-i\omega N t_0})\right| \tag{4}$$

Equating the maximum values of Eq. (3) and (4), the relation of A_l and V can be expressed by $A_l = 2V / t_0$.

Much computational effort is required to calculate the critical elastic-plastic response under the multi-cycle sine wave (harmonic excitation) [4, 5]. However, using a multi impulse as a substitute for such input enables the simple expression of complex elastic-plastic responses because only the free vibration appears under impulse input and an approach based on the energy balance law is easily applied (Fig. 1(b)). Moreover, the critical resonant frequency can be found automatically for the gradually increasing input level when using the multi impulse (Fig. 2). Fig. 3 illustrates the Fourier amplitudes of $\ddot{u}_g^{\mathrm{MI}}$ and $\ddot{u}_g^{\mathrm{MSW}}$ in the case of $N = 20$ as an example.

3. Model and Parameters

The complicated model of a nonlinear base-isolated building considering soil-structure interaction is first modeled into a 2DOF system (SDOF superstructure and base-isolation story) on a swaying-rocking spring-dashpot system as shown in Fig. 4 [12]. The base-isolation story is assumed to be composed of lead rubber bearings with bilinear hysteresis. The masses of the superstructure, the base-isolation story and the base mat are denoted by m_U, m_I, m_0 and the corresponding mass moments of inertia are denoted by I_U, I_I, I_0. The stiffnesses and damping coefficients of the superstructure and the base-isolation story are denoted by k_U, k_I, c_U, c_I. Let d_{yI} and α_I denote the yield deformation and the post-yield stiffness ratio to the initial stiffness at the base-isolation story. The swaying-rocking stiffnesses and damping coefficients of the spring-dashpot system of the ground are denoted by k_H, k_R, c_H, c_R. H_U, H_I are the height of the masses of the superstructure and the base-isolation story from the base mat. The swaying-rocking spring-dashpot parameters are evaluated by the formula presented in [13]. The 10-story model, which was used in [12], is considered again in this paper.

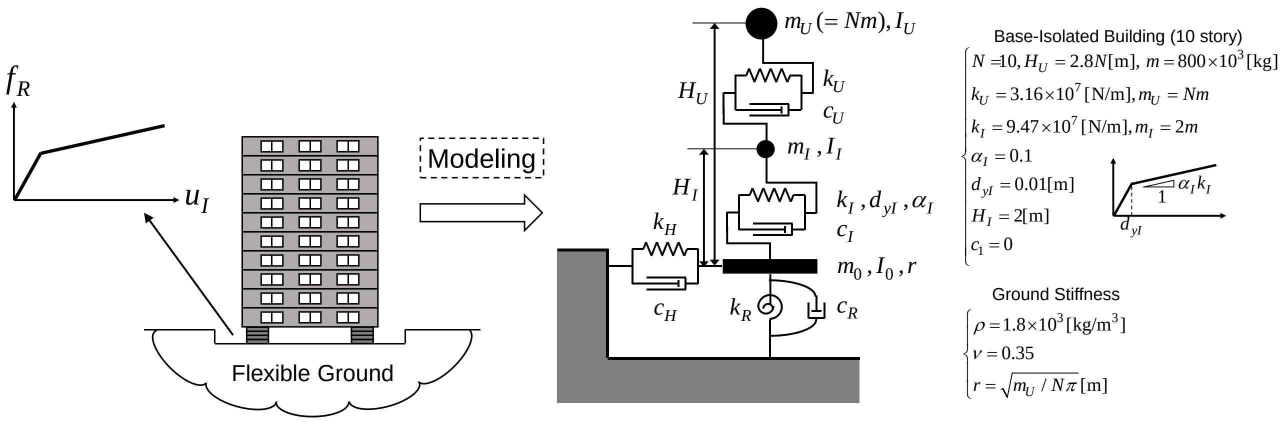


Fig. 4 – 2DOF base-isolated building model on swaying-rocking spring-dashpot system.

4. Transformation of the System into SDOF System

The 2DOF system consisting of a SDOF superstructure and a base-isolation story on rigid ground can be transformed into a SDOF system by deleting the degree of freedom just above the base-isolation story [12]. Some modifications should be made in the case of dealing with long-duration motions. This is because the response value is more sensitive to the model parameter such as damping and mass than in the case of dealing with short-duration motions.

The mass of the transformed SDOF system was regarded equal to the mass of superstructure in [12]. Therefore, the undamped natural circular frequency of the SDOF is expressed as

$$\omega_e = \sqrt{k_I k_U / \{m_U (k_I + k_U)\}} \tag{5}$$

On the other hand, the undamped natural circular frequency of the 2DOF system is expressed by

$$\omega_1^2 = \frac{\{k_U (m_U + m_I) + k_I m_U\} - \sqrt{\{k_U (m_U + m_I) + k_I m_U\}^2 - 4 m_I m_U k_I k_U}}{2 m_I m_U} \tag{6}$$

These undamped natural circular frequencies correspond when taking the limit of Eq. (6) as m_I approaches 0. However in the case where m_I / m_U is not small, $\omega_e' = \sqrt{k_I k_U / \{(m_I + m_U)(k_I + k_U)\}}$ corresponds to ω_1 better than ω_e when k_I is smaller than k_U, as shown in Fig. 5. Therefore, it is desirable to regard the value of the mass of the transformed SDOF system as $(m_I + m_U)$.

The damping coefficient of the transformed SDOF system is expressed as

$$c_e = \frac{(k_I c_U + k_U c_I)(k_I + k_U) - (k_I k_U - \omega_e^2 c_I c_U)(c_I + c_U)}{(k_I + k_U)^2 + \omega_e^2 (c_I + c_U)^2} \tag{7}$$

For the large input level, the second stiffness range of the base-isolation story in the response greatly surpasses the initial elastic stiffness range. However, Eq. (7) uses the initial elastic stiffness, and it does not evaluate the damping ratio well. Therefore, it is desirable to use the value of the second stiffness of the base-isolation story, i.e.

$$c_{e2} = \frac{(\alpha_I k_I c_U + k_U c_I)(\alpha_I k_I + k_U) - (\alpha_I k_I k_U - \omega_{e2}^2 c_I c_U)(c_I + c_U)}{(\alpha_I k_I + k_U)^2 + \omega_{e2}^2 (c_I + c_U)^2}, \quad \omega_{e2} = \sqrt{\frac{\alpha_I k_I k_U}{(m_I + m_U)(\alpha_I k_I + k_U)}} \tag{8}$$

The total system, namely, the 2DOF shear building model supported by the swaying-rocking spring-dashpot system is transformed into a SDOF system through a two-stage procedure (Fig. 6).

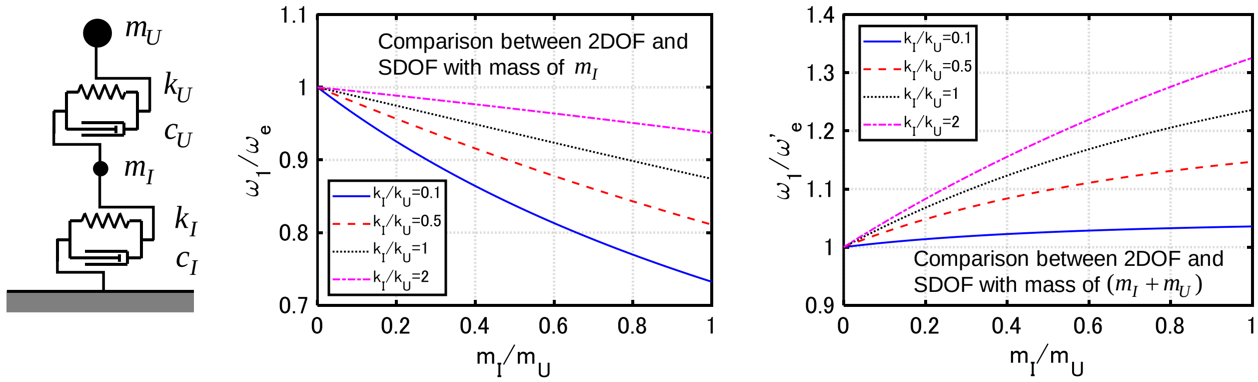


Fig. 5 – Comparison of undamped natural circular frequencies of SDOF and 2DOF systems for various numbers of stories of buildings (smaller value of m_I / m_U indicates taller building)

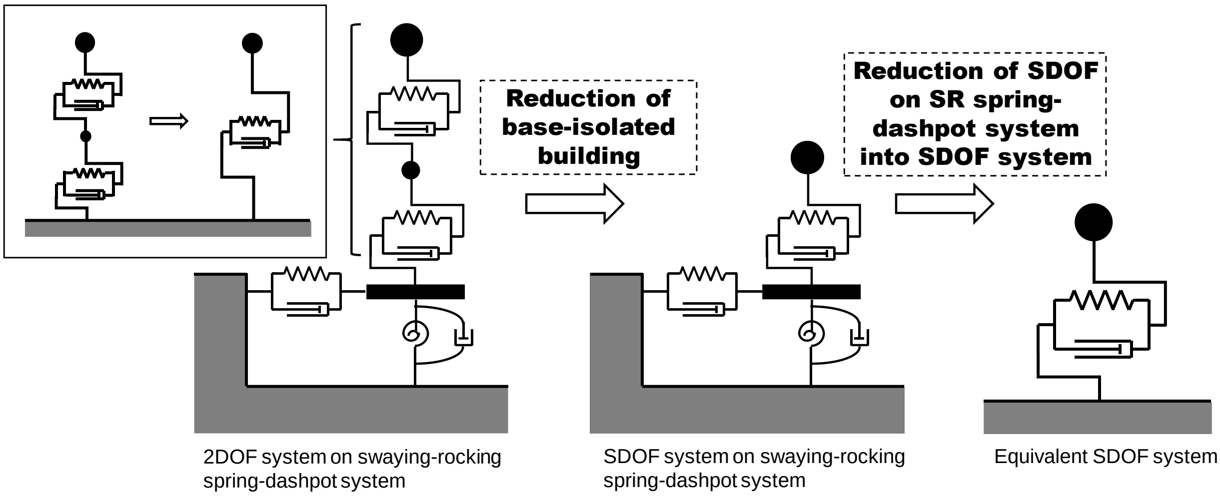


Fig. 6 – Transformation of whole model into SDOF system through two-stage procedure

Source: [12]

5. Explicit Expression on Critical Elastic-Plastic Response of Base-Isolation Story

In the previous work [6], an explicit expression on the peak deformation of a damped SDOF system of bilinear hysteresis under the critical multi impulse was derived. Applying this expression to the finally transformed SDOF system, the total deformation $u_{\max}$ of the whole system can be calculated. Since the static series-spring is assumed when reducing the system into the SDOF system, the corresponding maximum deformation $u_{I\max}$ of the base-isolation story can be derived as follows.

$$u_{I\max} = \begin{cases} (k/k_I)u_{\max} & \text{(CASE 0)} \\ u_{\max} - \{k_I d_{yI} + \alpha k(u_{\max} - \frac{k_I}{k} d_{yI})\}(\frac{1}{k_U} + \frac{1}{k_H} + \frac{H_U{}^2}{k_R}) & \text{(CASE 1, 2)} \end{cases} \tag{9}$$

where k and α are the initial stiffness and the second stiffness ratio to the initial stiffness of the finally transformed SDOF system. These three cases are classified depending on the plastic deformation level. In CASE 0, the model remains elastic. In CASEs 1 and 2, each impulse acts at the point of zero restoring-force in the ranges of the initial stiffness or the second stiffness, respectively.

The maximum values of the superstructure deformation, the swaying displacement and the angle of rotation of the base mat can be calculated in the same way.

6. Accuracy Check of the Proposed Method by Time-History Response Analysis

In order to investigate the reliability and validity of the proposed expression under the multi impulse with the velocity V, the time-history response analysis has been performed for the 2DOF system on the swaying-rocking spring-dashpot system under the multi impulse. In the time-history analysis, the time interval t_0^c which maximizes the deformation of the base-isolation story was adopted. This time interval t_0^c was obtained by changing the time interval t_0 parametrically.

Fig. 7(a)-(e) show the comparison of the maximum deformation of the base-isolation story of the transformed SDOF system on various grounds. Four types of ground stiffness are considered here. Table 1 shows the parameters of the finally transformed SDOF system. It can be observed that the responses evaluated by the proposed method are accurate enough. It is also clarified that the decrease of ground stiffness increases the maximum deformation of the base-isolation story.

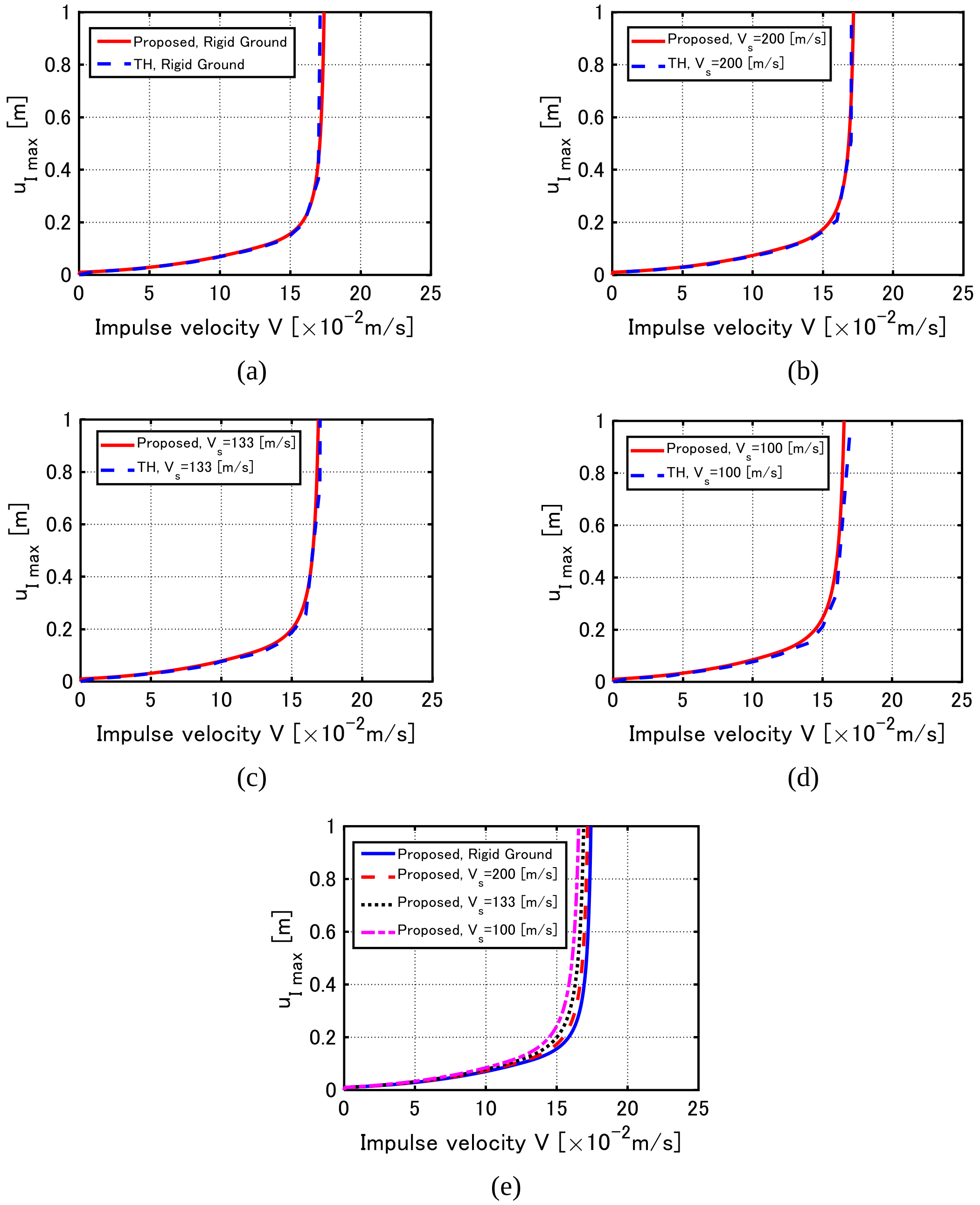


Fig. 7 – Maximum deformation of base-isolation story, (a) rigid ground, (b) $V_s = 200$[m/s], (c) $V_s = 133$[m/s], (d) $V_s = 100$[m/s], (e) all types of ground stiffness

Table 1 – Parameters of finally transformed SDOF systems

	k	α	h	d_y	V_y
Rigid Ground	7.29×10^{6}	0.126	3.22×10^{-5}	0.0130	0.0358
$V_s = 200$[m/s]	6.14×10^{6}	0.146	3.97×10^{-5}	0.0154	0.0390
$V_s = 133$[m/s]	5.12×10^{6}	0.171	5.65×10^{-5}	0.0185	0.0427
$V_s = 100$[m/s]	4.17×10^{6}	0.202	8.84×10^{-5}	0.0227	0.0474

In order to derive some important results about the soil-structure interaction, a formulation is introduced here for the relationship of the input level $V(u_{I\max}, k_g)$ with the maximum deformation of the base-isolation story, where $k_g = 1/\{(1/k_H) + (H^2/k_R)\}$ is the equivalent horizontal stiffness of the ground. It is assumed that the model is in the steady-state in CASE 2 as shown in Fig. 8. CASE 2 is the case where each impulse acts at the zero restoring-force point in the range of the second stiffness and the range of $u_{I\max} \geq 0.21$[m] corresponds to the case for the 10-story model. The damping ratio of the finally transformed SDOF system is treated as zero for simplicity. This assumption is valid because the damping ratio is very small as shown in Table 1. Nonlinear responses are dealt with 'directly' in this paper. Therefore, the damping ratio does not mean the equivalent damping ratio. Since the kinetic energy expressed in terms of the velocity v_c is equivalent to the maximum value of the strain energy of the whole model, v_c is chracterized by

$$\begin{aligned}&\frac{1}{2}(m_U + m_I)v_c^2 \\ &= 2\alpha_I k_I d_{yI}(u_{I\max} - d_{yI}) + \frac{1}{2\alpha_I k_I}\{\alpha_I k_I (u_{I\max} - d_{yI}) - f_{yI}\}^2 + \frac{1}{2}k_U u_{U\max}^2 + \frac{1}{2}k_g u_{g\max}^2\end{aligned} \tag{10}$$

where $u_{U\max} = \{k_I d_{yI} + \alpha_I k_I (u_{I\max} - d_{yI})\}/k_U$ and $u_{g\max} = \{k_I d_{yI} + \alpha_I k_I (u_{I\max} - d_{yI})\}/k_g$. Eq. (10) indicates that v_c is monotonically decreasing with respect to k_g. The energy balance law at the impulse acting point and the maximum deformation point leads to

$$(1/2)(m_U + m_I)(V^2 + 2v_c V) = 2(1-\alpha_I)k_I d_{yI}(u_{I\max} - d_{yI}) \tag{11}$$

Then, V can be obtained by solving it,

$$V(u_{I\max}, k_g) = -v_c + \sqrt{v_c^2 + \frac{4(1-\alpha_I)k_I d_{yI}(u_{I\max} - d_{yI})}{m_U + m_I}} \tag{12}$$

The partial differentiation of V with respect to v_c provides

$$\frac{\partial V}{\partial v_c} = -1 + \frac{v_c}{\sqrt{v_c^2 + \frac{4(1-\alpha_I)k_I d_{yI}(u_{I\max} - d_{yI})}{m_U + m_I}}} \tag{13}$$

The second term of Eq. (13) is strictly smaller than one. Therefore Eq. (13) is strictly smaller than zero. From these results, it is found that V and k_g have an inversely proportional relation. In other words, the decrease of ground stiffness increases the maximum deformation of the base-isolation story under the condition of constant V.

Consider next $\lim_{u_{I\max}\to\infty} [V(u_{I\max}, \infty) - V(u_{I\max}, k_g)]$ as a soil-structure interaction effect indicator of base-isolation buildings. Regarding an undamped bilinear hysteretic SDOF system, the input level at which the response divergence phenomenon can occur is expressed as follows [14],

$$V = \frac{2-2\alpha}{\sqrt{\alpha}}\sqrt{\frac{k}{m}}d_y \tag{14}$$

From Eq. (14), $\lim_{u_{I\max}\to\infty} [V(u_{I\max}, \infty) - V(u_{I\max}, k_g)]$ can be obtained as

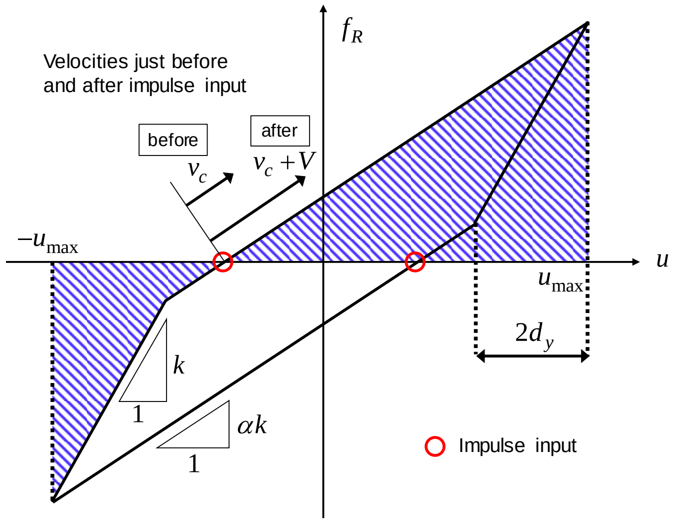


Fig. 8 – Restoring force-deformation relation of finally transformed SDOF systems under critical multi impulse in CASE 2

$$
\begin{aligned}
&\lim_{u_{I\max}\to\infty}\{V(u_{I\max},\infty)-V(u_{I\max},k_g)\}\\
&=\frac{2-2\alpha_e}{\sqrt{\alpha_e}}\sqrt{\frac{k_e}{(m_U+m_I)}}\frac{f_{yI}}{k_e}-\frac{2-2\alpha}{\sqrt{\alpha}}\sqrt{\frac{k}{(m_U+m_I)}}\frac{f_{yI}}{k}\\
&=\frac{2-2\alpha_e}{\sqrt{\alpha_e}}\sqrt{\frac{{k_I}^2}{(m_U+m_I)k_e}}d_{yI}-\frac{2-2\alpha}{\sqrt{\alpha}}\sqrt{\frac{{k_I}^2}{(m_U+m_I)k}}d_{yI}\\
&=\frac{2-2\alpha_e}{\sqrt{\alpha_e}}\sqrt{\frac{(k_I+k_U)k_I}{(m_U+m_I)k_U}}d_{yI}-\frac{2-2\alpha}{\sqrt{\alpha}}\sqrt{\frac{(k_Ik_U+k_Ik_g+k_Uk_g)k_I}{(m_U+m_I)k_Uk_g}}d_{yI}\\
&=\frac{2-2\alpha_e}{\sqrt{\alpha_e}}\sqrt{\frac{(k_I+k_U)k_I}{(m_U+m_I)k_U}}d_{yI}-\frac{2-2\alpha}{\sqrt{\alpha}}\sqrt{\frac{\{k_I+k_U(1+k_I/k_g)\}k_I}{(m_U+m_I)k_U}}d_{yI}
\end{aligned}
\tag{15}
$$

where k_e and α_e are the initial stiffness and the second stiffness ratio of the transformed SDOF system on a swaying-rocking spring-dashpot system. In this case $k \to k_e$ $(k_g \to \infty)$, $\alpha \to \alpha_e$ $(k_g \to \infty)$. The value of Eq. (15) depends on only the model parameter, not the input level. In CASE 2, the value of $\{V(u_{I\max},\infty)-V(u_{I\max},k_g)\}$ is almost constant as shown in Fig. 7. This is because the value of $(\partial u_{I\max}/\partial V)$ is quite large in CASE 2. Eq. (15) indicates that the effect of soil-structure interaction can be reduced by making k_I / k_g small enough.

Compared with the previous paper [12], the effect of the decrease of ground stiffness on the response under long-duration ground motions such as a multi impulse is larger than that under short-duration ground motions like a double impulse, which substitutes for pulse-like waves.

7. Comparison with the Result by the Equivalent Linearization Technique

In order to investigate the reliability and validity of the proposed method, a comparison with the result by Luco [1] is conducted in this section. The model parameters employed in [1] are used.

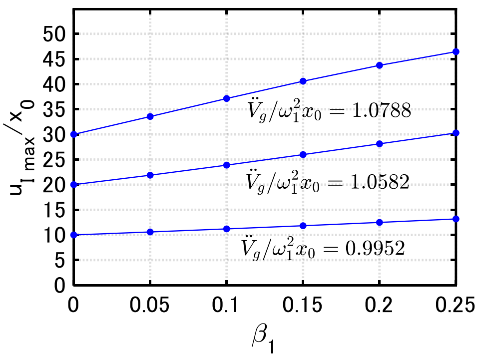
Luco [1] dealt with the harmonic excitation with constant acceleration amplitude, not with constant velocity amplitude. Some arrangements are needed to get the velocity V of the multi impulse equivalent to the acceleration amplitude $\ddot{V}_g$ of the harmonic excitation (see Section 2).

$$\ddot{V}_g = \omega \dot{V}_g = \omega(2/\pi)V \tag{16}$$

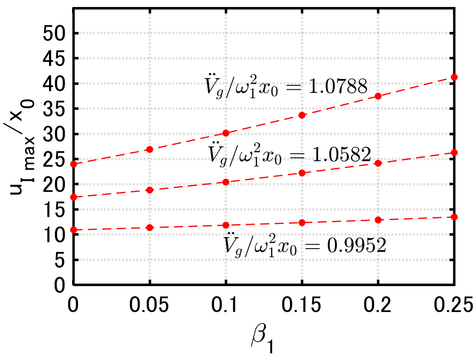
where $\dot{V}_g$ and ω are the velocity amplitude and the frequency of the harmonic excitation. To derive Eq. (16), an assumption is made that the harmonic excitation is critical under both the conditions of constant acceleration amplitude $\ddot{V}_g$ and of constant velocity amplitude $\dot{V}_g$. This assumption is valid in the case where the experienced second stiffness range surpasses the initial stiffness range. Eq. (16) means that the velocity amplitude V equivalent to $\ddot{V}_g$ depends on the input frequency ω although the velocity amplitude V equivalent to $\dot{V}_g$ does not. Thus, Eq. (16) implies that the effect of soil-structure interaction may appear clearly under the condition of constant acceleration while the effect of soil-structure interaction under the constant velocity amplitude is small.

Fig. 9(a) is the result of Luco [1] and Fig. 9(b) illustrates the maximum deformation of the base-isolation story calculated by the proposed method. β_1 indicates the relative initial stiffness of the isolators to that of the foundation. If the number of stories of the superstructure is ten, $\beta_1 = 0, 0.05, 0.15, 0.25$ are equal to $V_s = \infty$(rigid ground), 232,134,104[m/s]. Note that the values of ω in Fig. 9(a) are also used in Fig 9(b). Both results show that the decrease of ground stiffness increases the maximum deformation of the base-isolation story under the condition of constant acceleration amplitude of the input, although the result by the proposed method provides the maximum deformation smaller than the result of Luco.

Consider next the case of constant velocity amplitude of the input. Fig. 10(a) shows the critical maximum deformation of the base-isolation story calculated by the method by Luco [1]. It should be reminded that, since Luco didn't formulate the case of constant velocity amplitude, some modifications were added in order to deal with such case. Fig. 10(b) presents the maximum deformation calculated by the proposed method. Both results indicate that the ground stiffness does not influence the maximum deformation of the base-isolation story so much under the condition of constant velocity amplitude of the input, although the result by the proposed method provides the maximum deformation smaller than the result by the equivalent linearization technique.

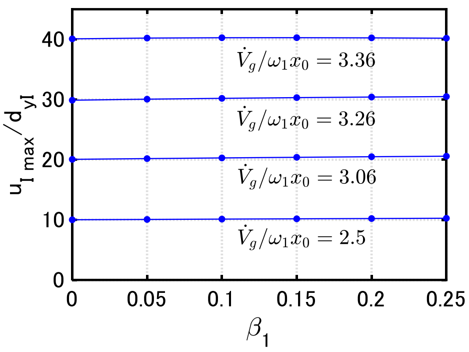


(a)

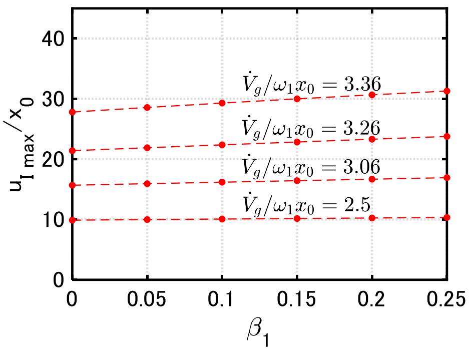


(b)

Fig. 9 – Critical maximum deformation of base-isolation story under condition of constant acceleration amplitude of input, (a) equivalent linearization (Luco [1]), (b) multi impulse



(a)



(b)

Fig. 10– Critical maximum deformation of base-isolation story under condition of constant velocity amplitude of input, (a) equivalent linearization, (b) multi impulse

8. Conclusions

The critical nonlinear response considering soil-structure interaction is investigated for a base-isolated building under a multi impulse as a representative of long-duration ground motions. The total system, namely, a 2DOF shear building model supported by the swaying-rocking spring-dashpot system, is transformed into a SDOF system through a two-stage procedure. Applying the expression on the peak deformation of a damped SDOF system of bilinear hysteresis under the critical multi impulse to the finally transformed SDOF system, the total deformation of the whole system can be calculated. Since a static series-spring is assumed when reducing the system into the SDOF system, the corresponding maximum deformation of the base-isolation story can be derived. It leads to the analytical clarification of the mechanism of soil-structure interaction effect. The conclusions are summarized as follows.

(1) The mechanism of soil-structure interaction effect for a base-isolated building under long-duration ground motions has been revealed analytically. The maximum deformation of the base-isolation story in the steady-state depends on the maximum strain energy stored in ground. The ground stiffness and the maximum strain energy have an inverse-proportional relation under a constant force. Therefore, the decrease of ground stiffness increases the maximum deformation of the base-isolation story.

(2) For the large input level (CASE 2), the response of the base-isolation story under the critical multi impulse almost diverges. Therefore, the value of $\{V(u_{I\,\max},\infty)-V(u_{I\,\max},k_g)\}$ is almost constant in CASE 2 (this value does neither depend on the input level nor $u_{I\,\max}$).

(3) It has been clarified that, while the decrease of ground stiffness increases the maximum deformation of the base-isolation story under the condition of constant acceleration amplitude of the input, the ground stiffness does not influence the maximum deformation of the base-isolation story so much under the condition of constant velocity amplitude of the input.

9. References

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