CONSISTENT MASS-SPRING MODEL FOR SEISMIC RESPONSE ANALYSIS CONSIDERING SOIL-STRUCTURE INTERACTION

M. R. RIAZ[1], M. HORI[2], Y. OTSUKA[3], J. A. S. C. JAYASINGHE[4], M. L. L. WIJERATHNE[5], and T. ICHIMURA[6]

[1]Ph.D. Candidate, Department of Civil Engineering, The University of Tokyo (Bunkyo, Tokyo 113-0032)
E-mail: rizwansamor@gmail.com
[2]Professor, Earthquake Research Institute, The University of Tokyo (Bunkyo, Tokyo 113-0032)
E-mail: hori@eri.u-tokyo.ac.jp
[3]Engineer, Tokyo Electric Power Services Co., Ltd. (Koto, Tokyo 135-0062)
E-mail: yuichi0otsuka@gmail.com
[4]Lecturer, Department of Civil Engineering, The University of Peradeniya (Peradeniya, Sri Lanka 20400)
E-mail: supun0chamara@gmail.com
[5]Associate Professor, Earthquake Research Institute, The University of Tokyo (Bunkyo, Tokyo 113-0032)
E-mail: lalith@eri.u-tokyo.ac.jp
[6]Associate Professor, Earthquake Research Institute, The University of Tokyo (Bunkyo, Tokyo 113-0032)
E-mail: ichimura@eri.u-tokyo.ac.jp

Soil-spring has been used in seismic structural analysis, when soil-structure interaction is taken into consideration. We seek to strengthen a methodology of determining the soil-spring properties, when a finite element solution for a model of massive solid elements is available. Attention is paid to consistency between the finite element model and the mass spring model that uses the soil-spring, so that the mass spring model is regarded as a mathematical approximation of the finite element model. Numerical experiments which use a finite element model and a mass spring model with a soil-spring are carried out, and it is shown that the mass spring model works as a fairly good approximated model of the finite element model.

Key Words : *soil-structure interaction, seismic structural response analysis, soil-spring model, meta-modeling theory, consistent modeling*

1. INTRODUCTION

Soil-Structure Interaction (SSI) is a fundamental issue of seismic structural response analysis for important structures such as a nuclear power plant building[1), 2), 3)]. A numerous amount of researches have been made on the evaluation of SSI for more accurate seismic response analysis[4), 5), 6)]. Conventionally, a soil-spring is employed for the evaluation of SSI, with a structure being modelled as a multiple mass spring system; a few or a few ten mass points, which are connected by springs, are used for a structure, and sway and rocking soil-springs are used for soil[7), 8)].

The mechanism of soil-spring is simple. When a structure is excited by input ground motion, it produces both displacement/rotation and force/bending moment at the base. The relation between the displacement/rotation and the force/moment is determined by the stiffness of the soil. Simple modelling of this relation is spring.

Latest computers are able to fully account for SSI when a soild element finite element model is analysed for a structure and soil (a soil-structure); a model which consists of more than one million solid elements can be constructed even for a soil-structure of complicated configuration[9), 10)]. The effects of SSI on the structural response are accurately computed when suitable modelling is made.

A methodology of determining properties of a soil-spring by analyzing a model of a soil-structure is established. However, it is limited to a case when a soil-structure is of simple configuration to obtain analytic solutions. It is necessary to strengthen this methodology in order to make use of numerical solutions of a soil-structure model of high fidelity.

In this paper, we first clarify SSI in the viewpoint of continuum mechanics. We then construct a soil-spring model, applying mathematical approximations, so that the soil-spring model provides an approximate solution to the mechanical problem as the solid element finite element. Numerical experiments which use a solid element model and a soil-spring model are carried out, in order to examine the usefulness of the soil-spring model that is constructed by the present methodology.

2. SSI IN VIEWPOINT OF CONTINUUM MECHANICS

For a soil-structure, continuum mechanics provides a well-posed mathematical problem which is expressed in terms of partial differential equations. The equations are point-wise, and do not consider SSI explicity. The effects of SSI on the structural reponse automatically appear in the solution, when suitable modelling is applied to a structure and soil as well as to the interface between them.

Solving point-wise differential equations for a soil-structure of complicated configuration is impossible without applying large scale numerical analysis. Hence, conventionally, a soil-structure of simplest configuration is used, so that analytic solutions (or series solutions) of the partial differential equations are obtained. A soil-spring is constructed by using these analytical solutions, and its properties are determined.

It should be emphasized that the methodology of determining the properties of the soil-spring is established for a soil-structure of simple configuration. However, the methodology is rarely employed for a soil-structure of complicated configuration. In our viewpoint, this is probably mainly because a numerical solution is not available for a soil-structure of complicated configuration. We also point out that another reason is that the validity of the methodology in being applied to a soil-structure of complicated configuration is not confirmed. Moreover, being lost is the understanding of the fundamental point of SSI, the effects of SSI appear in the solution of the continuum mechanics problem which does not have to take into accout SSI explicitly.

Meta-modeling theory[11), 12), 13)] is being proposed in order to strengthen a link between structural mechanics and continuum mechanics. The theory proves that some structural mechanics problems are mathematical approximation of continnum mechanics problem; for instance, beam problems which do use only Young's modulus are regarded as an approximation of continuum mechanics problems of elasticity which use both Young's modulus and Poisson's ratio. The meta-modeling theory is simple in principle. It only uses a Lagrangian of continuum mechanics, from which a continuum mechanics problem or a structural mechanics problem is derived by applying no/some mathematical approximations.

Extending the meta-modeling theory from a strcutre to a soil-structure, we are able to construct a mass spring model which uses a soil-spring; the properties of the soil-spring are fully determined even for a soil-structure of most complicated configuration. Conventionally, a solution of a continuum mechanics problem of a simple soil-structure is approximated to construct a soil-spring. We now approximate a continuum mechanics problem of a complicated soil-structure to determine a soil-spring of a mass spring model.

3. META-MODELING THEORY

In meta-modeling theory, the variational problem using a Lagrangian is called as physical problem, and obtaining an approximated solution of this physical problem is called modeling. Many kinds of modeling can be made for the same physical problem. Hence, a theory of making such modeling is called meta-modeling in the sense that modeling is modeled. In the meta-modeling theory, solving the same physical problems is called as consistency of modeling.

An exact solution of the Lagrangian variation problem is computed by computing a solid element model of high fidelity. A solution of modeling is, by definition, an approximate solution of this exact solution. It is thus obvious that the solution of less approximated modeling has higher accuracy. We should mention that in solving a physical problem, we have to compare the accuracy of the solution by comparing the experimental or observed data. In meta-modeling, the exact solution of the Lagrangian problem must be compared with the experimental or observed data. For the approximated solution that is obtained from modeling, it is sufficient to compare with the exact solution, since modeling is mathematical approximation.

In seismic response analysis considering SSI, an analysis domain of a soil-structure is a domain containing a structure and soil. More precisely, denoting the domain of a structure and soil by S and G, respectively, we denote the domain of the soil-structure by V the union of S and G; see **Fig. 1**. G is a finite region with an appropriate boundary condition with which there does not occur unnecessary reflection of seismic waves. Initial boundary value problem for a displacement function of time and space, $\boldsymbol{u}(\boldsymbol{x},t)$ in V, is a mathematical problem of continuum mechanics, which is analysed numerically by FEM. Here, bold indicates a vector (or tensor quantity), and $\boldsymbol{x}$ and t are spatial coordinate and time, respectively. To target a displacement function of the three-dimensional vector, the use of solid elements is assumed.

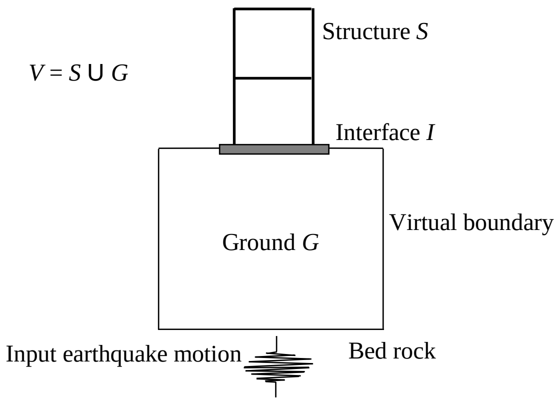

Fig. 1: Analysis area for the seismic response analysis considering SSI

Assuming small deformation and linear elasticity, the mathematical problem of $\boldsymbol{u}$ in V can be set as a variational problem of the following Lagrangian:

$$\mathcal{L}[\boldsymbol{v},\boldsymbol{\epsilon}] = \int_V \frac{1}{2}\rho\boldsymbol{v}\cdot\boldsymbol{v} - \frac{1}{2}\boldsymbol{\epsilon}:\boldsymbol{c}:\boldsymbol{\epsilon}\,\mathrm{d}v, \qquad (1)$$

where $\boldsymbol{v}$ and $\boldsymbol{\epsilon}$ are velocity and strain, respectively, ρ and $\boldsymbol{c}$ are density and elasticity tensor, respectively, and $\cdot$ and $:$ are inner product and the second order contraction, respectively. For simplicity, the variable $\boldsymbol{x}$ amd t are excluded. The value of ρ and $\boldsymbol{c}$ changes in soil and structure so these are $\rho(\boldsymbol{x})$ and $\boldsymbol{c}(\boldsymbol{x})$. Variational problem of the analysis domain in question is the following equation.

$$\delta\int_T \mathcal{L}[\dot{\boldsymbol{u}}, sym\{\boldsymbol{\nabla u}\}]\mathrm{d}t = 0. \qquad (2)$$

Here $\dot{\boldsymbol{u}}$ and $\boldsymbol{\nabla u}$ are the temporal derivative and gradient of $\boldsymbol{u}$, *sym* is the symmetric part of the second order tensor and T is an appropriate time domain.

Based on the meta-modeling theory, it shall be sufficient to mathematically approximate $\boldsymbol{u}$, in order to construct a mass spring model which is consistent with the continuum mechanics problem. Approximating a function mathematically means that the form of a function is specified. And a mathematical problem of a mass spring model is derived from the variational problem of $\mathcal{L}$ for the specified function of $\boldsymbol{u}$. It should be emphasized that the mass spring model is derived from $\mathcal{L}$ without making any physical assumptions. Adding a physical assumption means changing $\mathcal{L}$, and a different physical problem is constructed, which is not consistent with the continuum model.

We must be aware of the three points in making mathematical approximations for a mass spring model. The first point is that displacement of structure and soil can be considered separately. However, continuity at the interface, denoted by I, between the two regions, S and G, must be guaranteed. The second point is that ground motion amplified at the free surface is input into the base of the structure. The third point is that matchnig the natural frequency and the corresponding mode between the mass spring model and the continuum mechanics problem is needed to make higher accuracy of the mass spring model.

4. MASS SPRING MODEL BASED ON META-MODELING THEORY

(1) Condition at interface

In general, the natural frequency of the structure changes in the presence of soil, because of SSI. However, introduction of rigid foundation at the interface of the structure and the soil removes this change. We regard the interfrace, I, as rigid body, and express the form of $\boldsymbol{u}$ at I in terms of rigid body translation and rotation, denoted by $\boldsymbol{u}^*$ and $\boldsymbol{\theta}^*$, respectively, i.e.

$$\boldsymbol{u}(\boldsymbol{x},t) = \boldsymbol{u}^*(t) + \boldsymbol{\theta}^*(t)\times\boldsymbol{x} \qquad \text{on } I, \qquad (3)$$

where $\times$ is the cross (outer) product. We assume that rotation is small and the coordinate origin is at the center of I.

Equation (3) can be regarded as boundary condition for displacement function of structure S because I is a part of the boundary of S. As a nature of boundary value problem, we have to consider a homogeneous solution, which satisfies

$$\rho\ddot{\boldsymbol{u}} + \boldsymbol{\nabla}.(\boldsymbol{c}:\boldsymbol{\nabla u}) = \boldsymbol{0} \quad \text{in } S,$$

and $\boldsymbol{u} = \boldsymbol{0}$ on I. As seen, a set of the above differential equation and the boundary condition poses a homogeneous problem, and a non-trivial solution of this problem is the mode for a certain natural frequency, i.e. a solution of

$$\rho\omega^2\boldsymbol{\phi}(\boldsymbol{x}) + \boldsymbol{\nabla}.(\boldsymbol{c}:\boldsymbol{\nabla\phi}(\boldsymbol{x})) = \boldsymbol{0},$$

where ω and $\boldsymbol{\phi}$ are the natural frequency and the corresponding mode. The structure vibrates with displacement at the base fixed, and the natural frequency and natural modes can be determined without considering SSI. Note that conditions of Eq. (3) must be imposed on a particular solution of the displacement functions of S and G, so that continuity of displacement is guaranteed.

(2) Approximated displacement function

In the meta-modeling theory, the displacement function $\boldsymbol{u}$ used for $\mathcal{L}$ is approximated, and a mathematical problem for the approximated function is derived from the variation of the resulting $\mathcal{L}$. For a consinstent mass spring model, $\boldsymbol{u}$ in the structure and soil domains is approximated as follows

$$=\begin{cases}\boldsymbol{b}^*(t)+\boldsymbol{U}(t)+\boldsymbol{\Theta}(t)\times\boldsymbol{x}+\boldsymbol{u}^S(\boldsymbol{x},t) & in\ S,\\ \boldsymbol{b}(\boldsymbol{x},\boldsymbol{t})+\boldsymbol{u}^G(\boldsymbol{x},\boldsymbol{t}) & in\ G,\end{cases} \quad (4)$$

where $\boldsymbol{b}$ is the amplified ground motion in *G* without the presence of *S*; $\boldsymbol{u}^G$ is the additional displacement to $\boldsymbol{b}$ by the presence of *S*; $\boldsymbol{b}^*$ is the rigid body translation at the interface *I* induced by $\boldsymbol{b}$; $\boldsymbol{U}$ and $\boldsymbol{\Theta}$ are, respectively, the rigid body translation and rotation of *I* induced by SSI; and $\boldsymbol{u}^S$ is the displacement induced in the structure by $(\boldsymbol{b}^*+\boldsymbol{U}+\boldsymbol{\Theta}\times\boldsymbol{x})$. Among these displacements, $\boldsymbol{b}$ and $\boldsymbol{b}^*$ are computed separately, and unknown functions are $\boldsymbol{u}^S(\boldsymbol{x},t)$, $\boldsymbol{u}^G(\boldsymbol{x},t)$, $\boldsymbol{U}(t)$ and $\boldsymbol{\Theta}(t)$.

As mentioned in the preceding subsection, the use of a mode of the structure in discretizing $\boldsymbol{u}$ is a reasonable choice, in order to match the natural frequency and mode of the mass spring model with those of the continuum mechanics problem; they are the dynamic characteristics of the structure. Denoting by $\boldsymbol{\phi}^\alpha$ the α^{th} mode of the structure, we now approximate $\boldsymbol{u}^S$ as

$$\boldsymbol{u}^S(\boldsymbol{x},t)=\sum_\alpha a^\alpha(t)\boldsymbol{\phi}^\alpha(\boldsymbol{x})\,. \quad (5)$$

Here a^α is the amplitude of the α^{th} mode. In the mass spring model, $\boldsymbol{u}^G$, the displacement of soil, is induced when *I* is given forced displacement. Denoting by $\boldsymbol{\eta}^{U\alpha}$ and $\boldsymbol{\eta}^{\Theta\alpha}$ soil displacements that are induced by forced vibration of $\boldsymbol{U}$ and $\boldsymbol{\Theta}$, respectively, $\boldsymbol{u}^G$ is set as

$$\boldsymbol{u}^G(\boldsymbol{x},t)=\sum_\alpha U^\alpha(t)\boldsymbol{\eta}^{U\alpha}(\boldsymbol{x})+\Theta^\alpha(t)\boldsymbol{\eta}^{\Theta\alpha}(\boldsymbol{x}). \quad (6)$$

Here U^α and Θ^α are amplitudes of $\boldsymbol{\eta}^{U\alpha}$ and $\boldsymbol{\eta}^{\Theta\alpha}$, respectively.

With substitution of Eqs. (4), (5) and (6) into Eq. (1), a Lagrangian for the SSI system is obtained. We consider the simplest case of one mode ($\alpha=1$) for the mass spring model, together with the rigid body and soil-spring. The final expression for the Lagrangian is given as follows:

$$\begin{aligned}\mathcal{L}[a,U,\Theta]&=\tfrac{1}{2}M^S\dot{a}^2-\tfrac{1}{2}K^Sa^2+M^b\dot{b}^*\dot{a}+\\ &\tfrac{1}{2}M^{UU}\dot{U}^2+\tfrac{1}{2}M^{\Theta\Theta}\dot{\Theta}^2+M^{U\Theta}\dot{U}\dot{\Theta}-\tfrac{1}{2}K^{UU}U^2-\\ &\tfrac{1}{2}K^{\Theta\Theta}\Theta^2-K^{U\Theta}U\Theta+M^U\dot{a}\dot{U}+M^\Theta\dot{a}\dot{\Theta}+\\ &\tfrac{1}{2}M\dot{U}^2+\tfrac{1}{2}M^I\dot{\Theta}^2+M^{SU\Theta}\dot{U}\dot{\Theta},\end{aligned} \quad (7)$$

where M^S, M^b, M^{UU}, $M^{\Theta\Theta}$and $M^{U\Theta}$ in above Lagrangian are computed as follows:

$$M=\int_{S/G}\rho\,X\cdot Y\,\mathrm{d}v$$

by replacing *X* with $\boldsymbol{\phi}$, $\boldsymbol{b}$, $\boldsymbol{\eta}^U$ or $\boldsymbol{\eta}^\Theta$ and *Y* with $\boldsymbol{\eta}^U$ or $\boldsymbol{\eta}^\Theta$, and using the corresponding structure or soil domain; similarly K^S, K^{UU}, $K^{\Theta\Theta}$ and $K^{U\Theta}$ are computed as follows:

$$K=\int_{S/G}\boldsymbol{\nabla}X:\boldsymbol{c}:\boldsymbol{\nabla}Y\,\mathrm{d}v$$

M is the total mass of the structure and the remaining terms are as follows

$$M^U=\int_S\rho\,\phi\,\mathrm{d}v$$

$$M^\Theta=\int_S\rho\,\phi\times\boldsymbol{x}\,\mathrm{d}v$$

$$M^I=\int_S\rho\,\boldsymbol{x}\otimes\boldsymbol{x}\,\mathrm{d}v$$

$$M^{SU\Theta}=\int_S\rho\,\boldsymbol{x}\,\mathrm{d}v$$

(3) Governing equation for the 1D mass spring model

For simplicity, consider a ground structure system installed in a uniform soil. Considering the orthogonal coordinates with x-axis and y-axis in the horizontal direction and *z*-axis in the vertical direction. Since the soil is uniform, $\boldsymbol{b}$ of the ground *G* is a function only of *z* having a component in the *x*-direction only. We consider only the *x*-direction response of the structure by considering rigid body translation *U* of boundary *I* is in the x direction only and rigid body rotation Θ only about the y-axis. The right side of the function of Eq. (4) is as follows.

$$\begin{aligned}\boldsymbol{u}^S&=a\phi(\boldsymbol{x})\boldsymbol{e}_x+(U(t)+\Theta(t)z)\boldsymbol{e}_x,\\ \boldsymbol{u}^G&=(U(t)\eta^U(\boldsymbol{x})+\Theta(t)\eta^\Theta(\boldsymbol{x}))\boldsymbol{e}_x,\end{aligned} \quad (8)$$

were, ϕ is the *x*-direction component of $\boldsymbol{\phi}^1$, the mode of the minimum natural frequency of the structure; η^U and η^Θ are the *x*-direction components of $\boldsymbol{\eta}^{U1}$ and $\boldsymbol{\eta}^{\Theta1}$, the soil displacement induced by rigid body translation and rigid rotation of *I*; and $\boldsymbol{e}_x$ is the unit vector in the x-direction. Note that the natural frequency of the rigid body translation and rigid rotation are the same as that of the structure.

Substituting Eq. (8) into Eq. (4) and substituting the resulting $\boldsymbol{u}$ into Eq. (1), $\mathcal{L}[a,U,\Theta]$ of Eq. (7), a functional of three functions, is obtained. The following governing equation is derived from the variational problem of $\delta\int\mathcal{L}\,\mathrm{d}t=0$:

$$[M][\{\ddot{u}\}+[K]\{u\}=-\{f\}. \quad (9)$$

Here the vectors $\{u\}$ and $\{f\}$ are

$$\{u\}=\begin{Bmatrix}u^S\\U\\\Theta\end{Bmatrix},\quad \{f\}=\begin{Bmatrix}M^{SU}\ddot{b}^*\\M\,\ddot{b}^*\\M^{SU\Theta}\,\ddot{b}^*\end{Bmatrix}.$$

And the matrices $[M]$ and $[K]$ are

$$[M] = \begin{bmatrix} M^S & M^U & M^\Theta \\ & M + M^{UU} & M^{SU\Theta} \\ sym & & M^I + M^{\Theta\Theta} \end{bmatrix},$$

$$[K] = \begin{bmatrix} K^S & 0 & 0 \\ & K^{UU} & 0 \\ sym & & K^{\Theta\Theta} \end{bmatrix}.$$

The explicit expressions for the components of the matrices are given in the preceding subsection. Equation (9) takes on the same form as the governing equations of a conventional mass spring with a soil-spring[14), 15)]; unknown functdions are displacement and rotation in the one direction, as shown in **Fig. 2**. It is seen that K^{UU} and $K^{\Theta\Theta}$, which are derived from the purely mathematical procedures, correspond to the soil-spring.

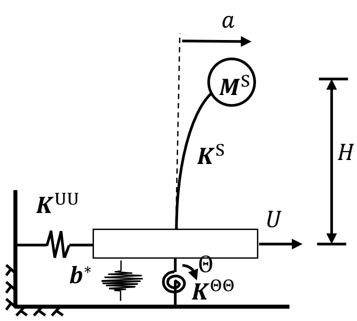

Fig. 2: Conventional mass-spring soil spring model

5. NUMERICAL EXPERIMENT

The target system consists of two storey building and uniform soil as shown in **Fig. 3** and **Fig. 4**. The target of the numerical experiement is to confirm that the response obtained from the developed mass-spring model is an appropriate approximation of the 3D FEM solution. Each floor of the structure comprises of concrete columns supporting rigid slab. Soil domain considered is in the shape of a cube. The structure rests directly on a rigid foundation laying on the surface without any embedment.

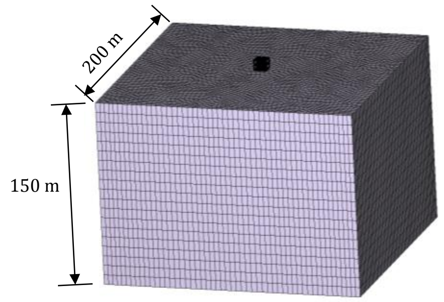

Fig. 3: Soil domain considered (200m×200m×150m)

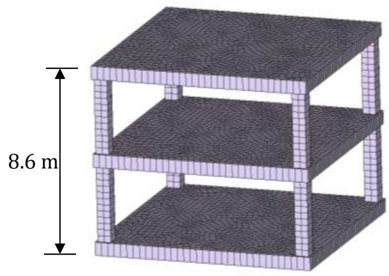

Fig. 4: Two storey structure considered

The physical properties of the materials used are listed in **Table 1**. Damping is not considered for this experiment.

Table 1 Physical properties of materials used in this study

	Column	Slabs	Soil	Plate
ρ (kg/m^3)	2400	25000	2500	0.01
E (GPa)	30	6000	0.96	1×10^6
ν	0.2	0.1	0.2	0.1

Two input ground motions are considered named GM1 and GM2 which along with their fourier spectrums are shown in **Fig. 5** and **Fig. 6**. The seismic waves are input at the bottom of the soil domain. If there is no structure, but the side surface of the y direction is free boundary, the sides of the x-direction coincides with the vertical direction of one-dimensional wave on the semi-infinite homogeneous soil. Considering sufficiently large soil domain and considering the influence of structure to be small, the one dimensional wave solution is imposed as boundary condition on the x face of the soil to avoid the reflection of the seismic waves.

To calculate mass and stiffness values for the mass-spring model, eigen mode ϕ of the structure and the amplified ground motion $\boldsymbol{b}$ are determined using the 3D FEM analysis. Time step used is 0.01sec. Minimum natural frequency and the corresponding mode of the structure and the soil domain is shown is **Fig. 7** and **Fig. 8** respectively. The displacement functions of the ground η^U and η^Θ are calculated from the dynamic analysis of the ground, which is vibrated by the rigid body translation and rigid rotation of I that oscillates at a frequency. In this experiment, this frequency is set equal to the minimum natural frequency of the structure. Setting a different natural frequency can also be studied.

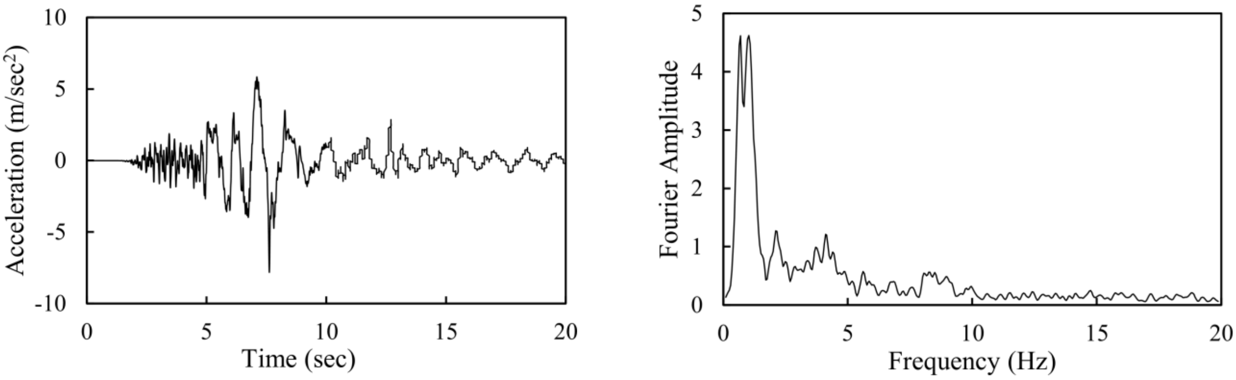

Fig. 5 Input ground motion GM1 and its fourier spectrum

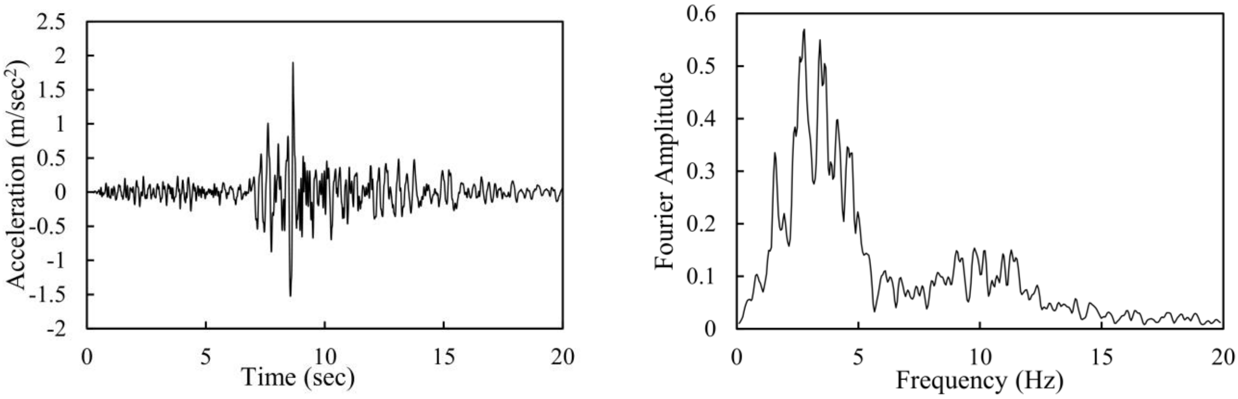

Fig. 6 Input ground motion GM2 and its fourier spectrum

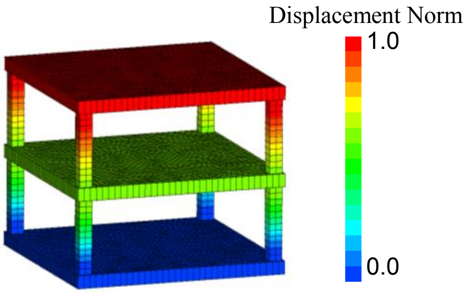

Fig. 7: Minimum natural frequency = 2.03 Hz

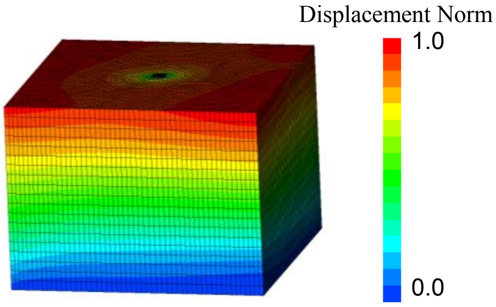

Fig. 8: Minimum natural frequency = 0.54 Hz

The mass and the spring constant is calculated using the expressions given in Section 2.2 and the values are shown in **Table 2**. Note that normalized eigen mode function is applied. **Table 3** shows the primary natural frequency of the finite element method models and the mass-spring model. It can be seen that these approximately coincide which is expected since the first natural mode of the structure has been used.

The comparison of time history of displacement response in the x-axis direction at the top of the structure for GM1 and GM2 is shown in **Fig. 9** and **Fig. 10** respectively. It can be seen that the solution of the mass-spring model is fairly consistent with the solution of the finite element method model.

Table 2 Mass and stiffness matrix parameters

Parameter	Value
M^S (kg)	2.90×10^6
M^U (kg)	2.45×10^6
M^θ (kg)	1.66×10^7
M (kg)	3.02×10^6

M^{UU} (kg)	8.96×10^9
$M^{SU\theta}$ (kg)	1.90×10^7
M^I (kg m^2)	1.32×10^8
$M^{\theta\theta}$ (kg m^2)	1.29×10^7
K^S (N/m)	4.78×10^8
K^{UU} (N/m)	1.57×10^{10}
$K^{\theta\theta}$ (N/m)	1.33×10^{11}

Table 3 Comparison of natural frequency

FEM model	Mass-Spring model
1.90	1.89

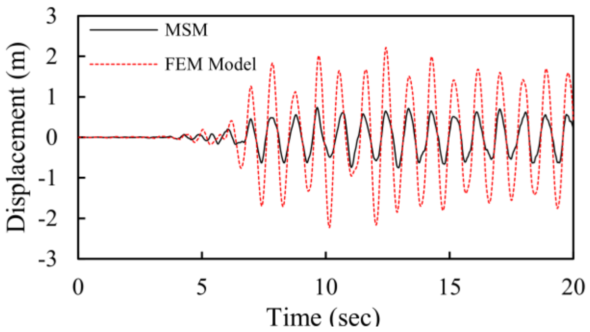

Fig. 9: Comparison of FEM and MSM for GM1

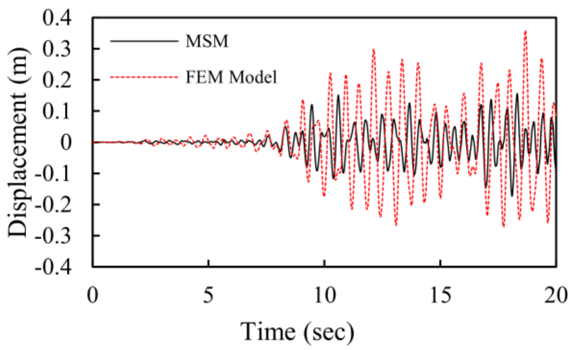

Fig. 10: Comparison of FEM and MSM for GM2

4. CONCLUSIONS

In this paper we clarify the basic concepts of mass-spring model and develop a mass-spring model which is consistent with FEM. The process to develop the consistent model starting from the Lagrangian of continuum mechanics is shown and the expressions to calculate the mass and spring constants for the mass-spring model are derived objectively. The simple numerical experiement performed shows that the response obtained from the developed mass-spring model is an appropriate approximation of the 3D FEM solution. In future the study aims at extending the mass-spring model to reproduce more than one modes and to consider the non-linear material behaviour.

REFERENCES

1) Wolf J. P.: *Dynamic Soil-Structure Interaction*, Prentice-Hall, Englewood Cliffs, New Jersy, 1985.
2) Scavuzzo R. J., Raftopoulos D. D. : A review of soil-structure interaction effects in the seismic analysis of nuclear power plants, *Nuclear Engineering and Design*, Vol. 28, pp. 400-413, 1974.
3) Roesset J.: Seismic design of nuclear power plants – where are we now?, *Nuclear Engineering and Design*, Vol. 182, No. 1, pp. 3-15, 1998.
4) Kausel E.: Early history of soil-structure interaction, *Soil Dynamics and Earthquake Engineering*, Vol. 30, No. 9, pp. 822-832, 2010.
5) Roesset J. : Soil structure interaction, the early stages, *Journal of Applied Science and Engineering*, Vol. 16(1), No. 1, pp. 1-8, 2013.
6) Gulkan P., Clough R. W.: *Developments in dynamic soil-structure interaction*, Proceedings of the NATO Advanced Study Institute on Developments in Dynamic Soil-Structure Interaction, Kemer, Antalya, Turkey, 1992.
7) Hirotani K., Ogata Y., Otake H., Iida J.: Simulation analysis of earthquake response of Onagawa nuclear power plant to the 2011 off the pacific coast of Tohoku earthquake, *The 15th World Conference on Earthquake Engineering*, 2012.
8) Tabatabaie M.: SASSI FE Program for Seismic Response Analysis of Nuclear Containment Structures, *International Workshop on Infrastructure Systems for Nuclear Energy*, 2008.
9) Yoshimura S., Hori M., Ohsaki M.: *High performance computing for structural mechanics and earthquake/tsunamic engineering*, Springer International Publishing, 2016.
10) Quinay P. E. B., Ichimura T., Hori M., Wijerathne M. L. L., Nishida A.: Seismic structural response analysis considering fault-structure system: Application to nuclear power plant structures, *Progress of Nuclear Science and Technology*, Vol. 2, pp. 516-523, 2011.
11) Hori M., Maddegedara L., Ichimura T., & Tanaka S. : Meta-Modeling for Constructing Model Consistent with Continuum Mechanics, *Journal of JSCE*, Vol. 2, No. 1, pp. 269-275, 2014.
12) Jayasinghe J. A. S. C., Hori M., Riaz M. R., Wijerathne M. L. L., Ichimura T.: Construction of consistent mass-spring model based on meta-mdeling theory for seismic response analysis of large scale bridge structures, *6th International Conference on Structural Engineering and Construction Management*, pp.75-83, 2015.
13) Wijerathne M. L. L., Wei X., Hori M., Ichimura T., Tanaka

S.: Automated meta-modeling of pipeline network for seismic performance analysis , *Journal of JSCE*, Vol. 70, No. 2, pp. 587-594, 2014.

14) Okada Y., Ogawa Y., Hiroshima M., Iwate T.: Application of sway-rocking model to retrofit design of bridges, *The 14th World Conference on Earthquake Engineering*, 2008.

15) Mikami A., Sawada T.: Time-domain identification system of dynamic soil-structure interaction, *The 13th World Conference on Earthquake Engineering*, 2004.

(Received September 2, 2016)