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Framework of Integrated Earthquake Simulation for Pipeline Network

M. Hori, T. Ichimura, M. L. L. Wijrathene and S. Tanaka
Earthquake Research Institute, The University of Tokyo
Japan

Abstract **This paper presents the framework of integrated earthquake simulation, which is a seamless simulation of all processes of earthquake hazard and disaster, for a pipeline network. Explained are the analysis model and method that are developed for the ground motion analysis and the seismic response analysis. As the core elements of these two analyses, large-scale dynamic 3D finite element analysis and metmodeling are developed. Examples of the integrated earthquake simulation for the pipeline network made by a prototype code are shown, and the results are discussed.**

Keywords— **integration of numerical simulation, earthquake wave propagation, seismic response anlaysis, meta-modeling**

I. Introduction

There is no question about maintaining high safety of pipeline networks against earthquake hazard since pipeline network serves as a lifeline for modern society and earthquake damage severely influences various activities in an urban area. However, it is an extremely difficult task to make the entire network, the total length of which reaches a few 100 or 1,000 km in a densely populated area, have the highest seismic performance uniformly. This is because ground condition changes and induced strong ground motion is concentrated on particular areas.

Seismic design is a core technology to maintain high safety of the pipeline network against earthquake hazard. Beside this, the earthquake damage assessment of an existing pipeline network is important to retrofit them or to prepare possible earthquake disaster induced by an expected large earthquake. The earthquake damage assessment is empirical based; the damage assessment uses fragility curves that are specified for the type of pipe. At this moment, there are no alternatives for the empirical damage assessment. More accurate assessment could be made if seismic response analysis that has been developed for a better seismic design is used instead of the fragility curves. In this seismic response analysis, estimate ground motion instead of design ground motion is input to a network and possible damage is analyzed.

To realize a more efficient damage assessment and repair plan, the authors are proposing the utilization of integrated earthquake simulation (IES) [1, 2]; see Fig. 1. IES is a seamless simulation of earthquake hazard and disaster for an urban area. Three processes, namely, the earthquake wave propagation process, the structure seismic response process and the repairing and recovering process, are simulated. For each process, suitable analysis models are constructed, and advanced numerical analysis methods, which is able to take advantage of high performance computing (HPC), are applied. It is a challenging task to develop a special IES for a pipeline network, which is aimed at making a more accurate damage assessment and a more efficient repair plan by making full use of available numerical analysis methods.

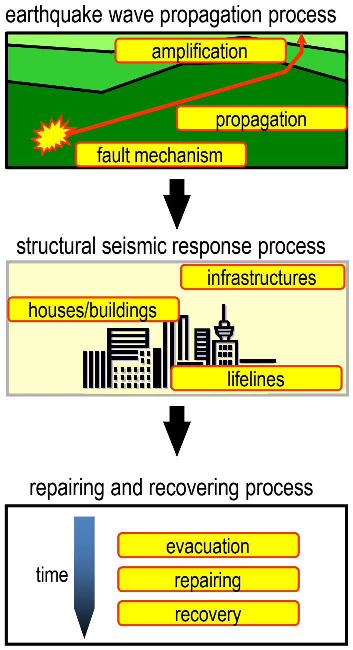


Fig. 1 Overview of IES.

In this paper, we present the framework of IES for the pipeline network (IES_PN). Although a seamless simulation is not achieved, we have developed the ground motion analysis, which is a part of the analysis of earthquake wave propagation process, and the seismic response analysis for the pipeline network. The contents of the paper are as follows: In Section 2, we summarize the software architecture of IES, on which IES_PN is based on. In Sections 3 and 4, we explain two modules of the ground motion analysis and the seismic response analysis. Detailed explanations are made for the analysis model and methods of these modules. Results of test simulations are presented and discussed in Section 5. Some concluding remarks are drawn in Section 6.

II. Architecture of IES

As software architecture, IES employs a layer structure which consists of three layers, namely, the data layer, the sim-

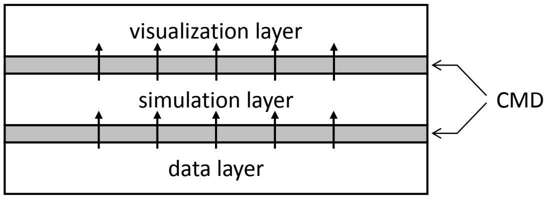


Fig. 2 Layer structure of IES. CMD is used for inter-layer communication.

ulation layer and the visualization layer [1]; see Fig. 2. These layers correspond to pre-process, solver and post-process of finite element method. The data layer includes a set of data and modules which convert the data to analysis models of various kinds. The simulation layer is a set of numerical analysis methods which input data from the data layer and output results to the visualization layer. The visualization layer is a set of visualization tools of two/three-dimensional or static/dynamic visualization.

For inter-layer communication, IES introduces Common Modeling Data (CMD). CMD is a format or a protocol for data. All data sets that are delivered to other layers must be converted to a common protocol of CMD. This is essential to maintain the easiness in coding or revising modules which are used in IES. If the number of components in the data, simulation and visualization layers are N, M and L, respectively, the number of converters for the inter-layer communication is $N \times M \times L$. If CMD is used, the number is reduced to $N + M + L$, even though the data conversion has to be made twice, i.e., one conversion from one component in one layer to CMD and another conversion from CMD to another component in another layer.

The simple layer structure of IES, which is supported by inter-layer communication of CMD, makes it easy to couple different simulations. The simulation layer has three groups of analysis methods which correspond to the earthquake wave propagation process, the structural seismic response process, and the repairing and recovering process. For instance, output of a module in the earthquake wave propagation process is used as input of a module in the structure seismic response process. In this manner, a module of the simulation layer can achieve fine granularity.

We should mention that, compared with coupling between the earthquake wave propagation process and the structural seismic response process, coupling between the structural seismic response process and the repairing and recovering process is difficult. A reason of this difficulty is that the repairing and recovering process uses a non-physical process simulation, while the earthquake wave propagation process and the structural seismic response process use physical process simulations. Moreover, various kinds of data are needed for the non-physical process simulation unlike the physical process simulation, which, in general, needs a large amount of data of a few kinds. Thus, current IES does not have automated system which enables us to carry out seamless simulation between the structural seismic response process and the repairing and recovering process.

III. Ground Motion Analysis

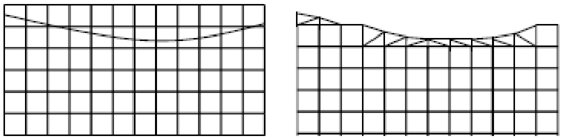
In general, seismic loading which is used for the seismic design of a pipeline network is ground strain, and traction is transmitted from soil to the pipe when there is displacement gap between them. The computation of ground strain induced by ground motion is of primary importance for the pipeline network, unlike other structures which need acceleration or velocity at their site as seismic loading. Therefore, IES_NP constructs a three-dimensional (3D) analysis model, which models underground structures as precisely as possible and dynamic finite element analysis [3, 4, 5, 6]. The problem size measured in terms of the degree of freedom is beyond 1,000,000. This section explain these analysis model and method.

A. 3D Underground Structure Model

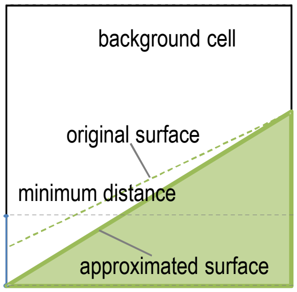
We assume that a set of boring data is given for a target area. While it is often a case that there are some contradictions among these data, we ignore them assuming that the structures consist of two or three distinct layers (which includes bedrock). The configuration of these layers is thus determined by interpolating and extrapolating the boring data about their depth.

Once interpolated and extrapolated configurations are given for each layer, there remains a more difficult task of constructing a solid element FEM model of high fidelity and quality; the configuration of the layers is precisely expressed and the number of ill-shaped elements is minimized. The authors are developing a model construction method which uses background cells, so that tetrahedral elements are used for cells which include the interfaces of different layers in them and hexagonal elements of identical shape are used for cells which consist of a single layer; see Fig. 3a). The results analysis model is hybrid of tetrahedral and hexagonal elements.

A quality of the hexagonal element is highest since it is cubic; a background cell is cubic. It is the tetrahedron element



a) ground surface made from background cell



b) approximation of surface layer configuration

Fig. 3 Underground structure modeling which uses background cell.

that may have bad quality; elements becomes flatter when the interface between two layers is closed to the top or bottom face of the background cell. Since the layer configuration is an approximation of the boring data, instead of introducing high quality elements, we change the layer configuration slightly. That is, we set the minimum distance between the interface and the cell's top or bottom face, and if the interface is located within the minimum distance too close, we shift down or up interface; see Fig. 3b). The minimum distance is set as 25 % of the background cell's edge length.

B. *3D Non-Linear FEM Analysis*

The governing equations that are solved for the ground motion analysis is the 3D wave equations for non-linear surface ground. The discretized form of the wave equation is given as

$$\left(\frac{4}{dt^2}\boldsymbol{M} + \frac{2}{dt}\boldsymbol{C}^{(n)} + K^{(n)}\right)\delta\boldsymbol{u}^{(n)} = \boldsymbol{f}^{(n)} - \boldsymbol{q}^{(n)} + \boldsymbol{C}^{(n)}\boldsymbol{v}^{(n-1)} + \boldsymbol{M}\left(\boldsymbol{a}^{(n-1)} + \frac{4}{dt}\boldsymbol{v}^{(n-1)}\right). \quad (1)$$

Here, $\delta\boldsymbol{u}$, $\boldsymbol{v}$, $\boldsymbol{a}$, $\boldsymbol{f}$ and $\boldsymbol{q}$ are a nodal vector for displacement increment, velocity, acceleration, force body force, respectively, $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are mass, dumping and stiffness matrices, dt is a time increment, and a number in the parenthesis indicates the number of the time step.

As a non-linear constitutive relation for soil, employed is a modified RO model and Masing Rule, which induces the change in $\boldsymbol{C}$ and $\boldsymbol{K}$ every time step. The most accurate numerical treatment of this non-linearity is implicit. For simplicity, however, IES_NP uses explicit treatment of $\boldsymbol{C}$ and $\boldsymbol{K}$ using a smaller value for dt. Note that $\boldsymbol{C}$ is computed in an element-wise manner, i.e., an element damping matrix, $\boldsymbol{c}^{(n)}$, is given as

$$\boldsymbol{c}^{(n)} = \alpha\boldsymbol{m} + \beta\boldsymbol{k}^{(n)}, \quad (2)$$

where $\boldsymbol{m}$ and $\boldsymbol{k}^{(n)}$ are the element mass and stiffness matrices, and the coefficients α and $\beta$are determined by minimizing

$$\int_{f_{min}}^{f_{max}} \left(h - \left(\frac{\alpha}{4\pi f} + \beta\pi f\right)\right)^2 df. \quad (3)$$

Here, f_{max} and f_{min} are the maximum and minimum value of the target frequency and h is the damping constant, so that the numerical damping in the target frequency, the term in the small parenthesis, becomes most closed to h.

The time integration for $\boldsymbol{u}$ that uses Eq. (1) is made by applying the Newmark-β method ($\beta = 1/4$and $\Delta = 1/2$), which is expressed as follows:

$$\boldsymbol{u}^{(n)} = \boldsymbol{u}^{(n-1)} + \delta\boldsymbol{u}^{(n)}. \quad (4)$$

The other nodal vectors is updated by using

$$\begin{aligned}\boldsymbol{v}^{(n)} &= -\boldsymbol{v}^{(n-1)} + \tfrac{2}{dt}\delta\boldsymbol{u}^{(n)},\\ \boldsymbol{a}^{(n)} &= -\boldsymbol{a}^{(n-1)} - \tfrac{4}{dt}\boldsymbol{v}^{(n-1)} + \tfrac{4}{dt^2}\delta\boldsymbol{u}^{(n)},\\ \boldsymbol{q}^{(n)} &= \boldsymbol{q}^{(n-1)} + \boldsymbol{K}^{(n)}\delta\boldsymbol{u}^{(n)}.\end{aligned} \quad (5)$$

Recall that Eq. (1), the linear matrix equation of $\delta\boldsymbol{u}^{(n)}$, is numerically solved for the above computed $\boldsymbol{q}^{(n)}$ and the previous step of $\boldsymbol{v}^{(n-1)}$ and $\boldsymbol{a}^{(n-1)}$. Most of numerical computation is used to solve Eq. (1).

IV. Seismic Response Analysis

Seismic response analysis of a pipeline network needs large scale computation when an entire network of an urban area is considered. The scale of computation increases if full consideration is taken for soil-structure interaction. To cope with the scale of the required numerical computation, we introduce *meta-modeling*. In this section, we explain meta-modeling first, and then provide examples of analysis model and method for the seismic response analysis of pipeline network.

A. *Meta-Modeling of Pipeline Network*

There are several classes of models for pipeline network, such as a simple beam model or a sophisticated model for advanced finite element method (FEM) analysis [7, 8, 9, 10]. Each modeling has its own advantages and disadvantages. Meta-modeling is a new concept of modeling, in order to utilize various classes of models for one structure, by fully using the advantages of each modeling. According to meta-modeling, models of different fidelity are constructed for one structure, and a suitable model is chosen for a specific setting; for instance, if high accuracy is needed, a model of high fidelity is used.

To maintain the consistency of generated models with a target structure, meta-modeling regards different modeling as different approximation of solving a common problem of the target structure, which is posed as a variational problem of continuum mechanics. To explain this, we consider the simplest case when the pipeline network consists of a linear elastic material, at quasi-static state. Denoting the network by V, we have the following variational problem of the displacement function $\boldsymbol{u}$ of V:

$$J[\boldsymbol{u}] = \int_V \tfrac{1}{2}\nabla\boldsymbol{u}:\boldsymbol{c}:\nabla\boldsymbol{u} - \boldsymbol{b}\cdot\boldsymbol{u}\,\mathrm{d}v, \quad (6)$$

where $\boldsymbol{b}$ is a body force vectors, $\boldsymbol{c}$ is an elasticity tensor, $\nabla\boldsymbol{u}$ stands for the gradient of , and $\cdot$ and $:$ are inner product and second order contraction, respectively.

A beam model is a case when $\boldsymbol{u}$ is approximated as

$$(u_1, u_2, u_3) = (-x_3 W', 0, W), \quad (7)$$

where $x_1$is the local coordinate along the network axis and x_3 is the vertical coordinate and W is a function of $x_1$only.

$$J[W] = \int_L \tfrac{1}{2}EI(W'')^2 - AbW\,\mathrm{d}x_1, \quad (8)$$

where L stands for the one-dimensional analysis domain of the beam model, (i.e., the line(s) corresponding to $(x_1, x_2, x_3) = (x_1, 0,0)$), E is Young's modulus, and A and I are the area and second moment of inertia. Note that vanishing of the variation of $L[W]$ yields a governing equation for a beam theory.

A shell model is constructed in a similar manner, just by approximating $\boldsymbol{u}$ with the displacement functions of the shell theory. That is, introducing the two-dimensional curvilinear coordinate system (ξ_1, ξ_2, ξ_3) in which the middle (or neutral) plane of the shell is $(\xi_1, \xi_2, \xi_3) = (\xi_1, \xi_2, 0)$, we have

$$(u_1, u_2, u_3) = (-W_{,1}\xi_3, -W_{,2}\xi_3, W), \quad (9)$$

where W is a function of (ξ_1, ξ_2) and an index followed by comma stands for the covariant derivative with respect to the corresponding coordinate. The functional becomes coordinate as

$$J[\boldsymbol{u}] = \int_S \left(\int \tfrac{1}{2} \nabla \boldsymbol{u} : \boldsymbol{c} : \nabla \boldsymbol{u} - \boldsymbol{b} \cdot \boldsymbol{u} \, \mathrm{d}\xi_3 \right) \mathrm{d}\xi_1 \mathrm{d}\xi_2, \quad (10)$$

where S is the middle plane of the shell and the covariant derivative is used for $\nabla \boldsymbol{u}$.

As summary, meta-modeling of the pipeline network that is used for IES_PN starts from Eq. (8), a beam model. Then, it goes to Eq. (9), a shell model. Finally, it ends at Eq. (6), a solid FEM model; see Fig. 4. As for visualization, Eq. (8) is used to easily present the distribution of cross sectional forces, so that overall (not local) response of the pipeline network is intuitively clear.

We have to mention that meta-modeling is harsh to structure mechanics in the sense that it regards a structure mechanics problem as an approximation of a continuum mechanics problem. However, the approximation made is smart since the structure mechanics problem is more easily solved than the continuum mechanics problems; the continuum mechanics problem is inherently three-dimensional, and cannot be solved without using large scale computation. Moreover, the continuum mechanics problem is free from singularity, which, in turn, shows the limitation in accuracy of structure mechanics.

The most accurate solution that is obtained for a solid element FEM model has a disadvantage of less transparency of the analysis results; for instance, the computed distribution of stress cannot be used for purpose of design, and it must be converted to the cross sectional force. To overcome this disadvantage, meta-modeling uses a model of low fidelity. That is, a solution of a high fidelity model is approximated as a solution of a low fidelity model. An intuitively clear and practically useful result is thus obtained from a model of high fidelity. The numerical results of the high fidelity model is large in amount, and often requires extensive post-processing. According to meta-modeling, only a solution of displacement function is processed to obtain approximated displacement, for which post-processing is easy as various tools are available.

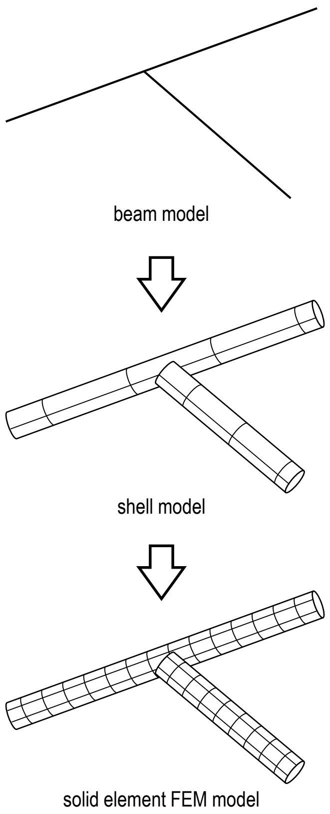


Fig. 4 Meta-modeling of pipeline network.

Meta-modeling has similarity to multi-scale analysis or smoothening techniques. It is able to provide a more accurate treatment by using models of higher fidelity. A difference of meta-modeling from the existing methods is that a different equation is used for a different model in meta-modeling, while the same governing equations are analyzed differently in the existing methods; the multi-scale analysis introduces a function which changes in different length-scale into a solution, and the smoothening techniques usually solve the same governing equations changing the domain size and spatial discretization size.

B. *Use of Commercial FEM Software*

Unlike the ground motion analysis, various kinds of commercial FEM software are available for a beam model, a shell model or a solid element FEM model of the pipeline network which are constructed according to meta-modeling. Since such software is well verified, quality of IES_PN is guaranteed if a suitable model is used. Comparing the results of the three models would help validation of the models.

The concept of meta-modeling is essentially important on the view point of validation, as it is a basis to construct three models which are mutually consistent in the sense that they use their own approximated displacement functions, $\boldsymbol{u}$, for a common functional, $J[\boldsymbol{u}]$ of Eq. (6). The distribution of displacement or stress must be similar for the different models except for connecting parts.

It is acceptable for IES_NP to use non-commercial programs which are developed to analyze one or all of the three models of the pipeline network. However, maintaining and updating the developed programs require continuous efforts; in particular, it needs a new skill to update the program when new hardware is available. The use of commercial software is a reasonable choice if it is maintained and updated. On the other hand, there are not many choices of commercial software which are able to solve large scale problems, taking full advantage of available HPC. Like the ground motion analysis, we are going to develop our own FEM program which has high scalability in parallel computation.

At this moment, modules in the simulation layer for the seismic response analysis are commercial software. As will be explained in the next section, it is the data conversion that must be developed for IES_PN, in order to construct three models from a given set of data of a pipeline network. A module of the data conversion must be maintained and updated by

IES_PN's developer; updating the program is inevitable when the data set is modified.

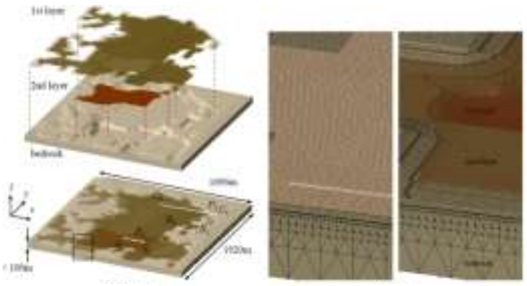
V. Examples of IES_PN

This section presents results made by trial simulations which is made by using IES_PN. We have to mention that coupling between the ground motion analysis and the seismic response analysis has not been finished. Coupling is made manually. First, we demonstrate accuracy of the ground motion analysis, comparing the simulated results with the observed data of ground motion. Then, we show example results of IES_PN.

A. *Ground Motion Analysis*

In order to validate the analysis model and method of the ground motion analysis, we construct a 3D underground structure model for an area of 1,696 x 1,920 m, using a set of elevation data and boring data; the detail information of these data, as well as the observed data for ground motion, will be presented in a paper which is being prepared. In Fig. 5, presented is the overview and close-up view of the constructed underground structure model. The EW, NS and UD directions are denoted by the x, y and z axes, respectively. As mentioned in Section 3, we use three layers, and the mechanical properties of these layers are summarized in Table 1.

We set the target frequency of the ground motion analysis as 2.5 Hz, so that strain induced by ground motion which influence a pipeline network can be accurately computed. The spatial discretization of the underground structure model is determined to satisfy the target frequency. It is known that for a second-order tetrahedron element, the element size is at least 1/5 of the wave length of the target frequency when a linear constitutive relation is used for soil. Since non-linear constitutive relation is employed in the present ground motion analysis, we set the minimum size of the element as 1/10 of the wave length. This spatial discretization results in a relatively large size of the problem; the degree of freedom is 32,509,107. The time increment is set as 0.005 sec.



a) overview b) close-up view

Fig. 5 Underground structure model.

Table 1. Mechanical properties of each layer.

	V_p m/sec	V_s m/sec	ρ kg/m^3	h_{max}	γ_r
1st layer	700	100	1500	0.23	0.007
2nd layer	1400	300	1800	0.23	0.001
bedrock	2100	700	2100	0.01	∞

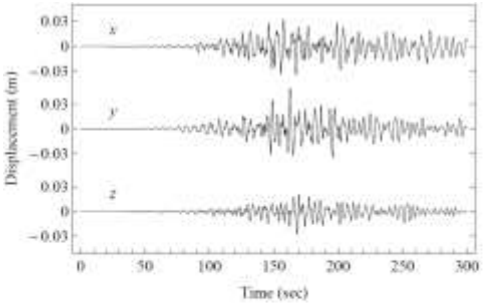
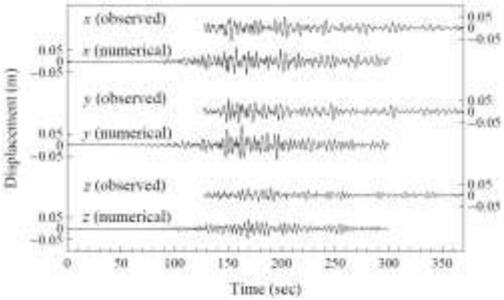


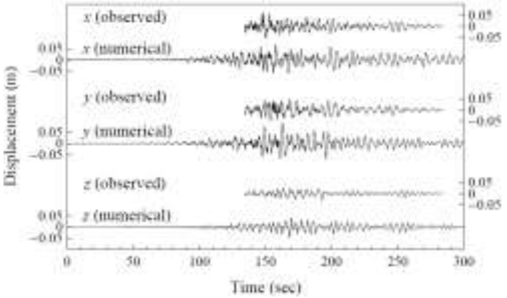
Fig. 6 Input ground motion at bedrock.

Displacement time series which is used as input ground motion at bedrock is shown in Fig. 6. This waveform is obtained by applying a trapezoid band path filter; the range is (0.1, 2.5) Hz and the width of the trapezoid is 0.1 Hz.

A PC cluster is employed for the whole computation of 60,000 time steps; CPU is Intel®Xeon® Processor X5680



a) P1



b) P2

Fig. 7 Comparison of computed ground motion with observed ground motion.

Table 2. Comparison of SI of observed ground motion and computed ground motion.

Point, Component		observed cm/sec	computed cm/sec
P_1,	x	25.6	28.2
	y	27.1	25.5
	z	6.25	9.35
P_2	x	9.92	15.9
	y	10.7	13.2
	z	6.53	9.28

with 6 cores, and one node has 2 CPU's and the cluster has 8 nodes, which are connected by INFINI band. The whole computation time is 1,107,495 sec or the average computation time for one step is 18.46 sec.

The comparison is made by using the observed data of ground motion at two points, denoted by P1 and P2 in Fig. 5. As will be explained in the paper, observed data lost some portions of records. The comparison of the waveform is presented in Fig. 7. As is seen, the computed ground motion agrees well with the observed ones at both the two points. SI-values are computed for these data, and are summarized in Table 2. The difference in SI is around 6 cm/sec at most.

B. *Example of IES_PN*

Long length and complexity of pipeline network makes it impossible to construct an analysis model manually. An automated model construction method is developed for models which are explained in the preceding section. In Fig. 8, three models of the pipe and the surrounding soil are presented; see Table 3. The method consists of the following three steps: 1) extracting information for each pipeline from an available data set; 2) interpreting information to determine the configuration of the analysis domain, L or S in Eq. (8) or (10), which includes junction connecting plural pipes; and 3) generating an analysis model according to the determined configuration.

Data of buried pipeline networks of various kinds are stored in a common Geographical Information System (GIS) in Japan. The general data include information about each pipe's geometrical, mechanical and structural properties. We thus need to extract this information from GIS. Since the GIS data are mainly used for visualization, the information has the following two major problems in being converted to an analysis model: 1) it has redundancies in defining the pipe configuration; and 2) it does not have connectivity information of connected pipes. The second problem is serious as it makes a problem of searching connected pipes have complexity of $O(N^2)$ with N being the number of pipes; a problem of this complexity is prohibitive for a large network.

Processing of network data is significantly faster if a graph data structure which has connectivity information is used. Therefore, information about structure properties of pipes are extracted from GIS and converted to a CMD of graph data structure; this CMD is called Network which consists of pipe nodes ordered in a sequential manner. Duplicated nodes are excluded, and the complexity in searching connection is reduced to $O(N)$. It should be emphasized that the difference in complexity in the connection search is a clear indicator of the advantage of converting GIS data into CMD.

In extracting information from GIS, there is a chance in which some parts of the network are missed to construct an analysis model; a chance is higher in dealing with to parts of complex configuration such as a loop or a multiple junction. The robustness in the data extraction is essentially important, since it is impossible to manually identify missing parts and to correct the corresponding part of the analysis model. To this end, a bitmap image of high resolution is made for the original GIS data and the extracted information, and they are compared in a pixel-wise manner. The robustness in the data extraction is confirmed by increasing resolution of the images.

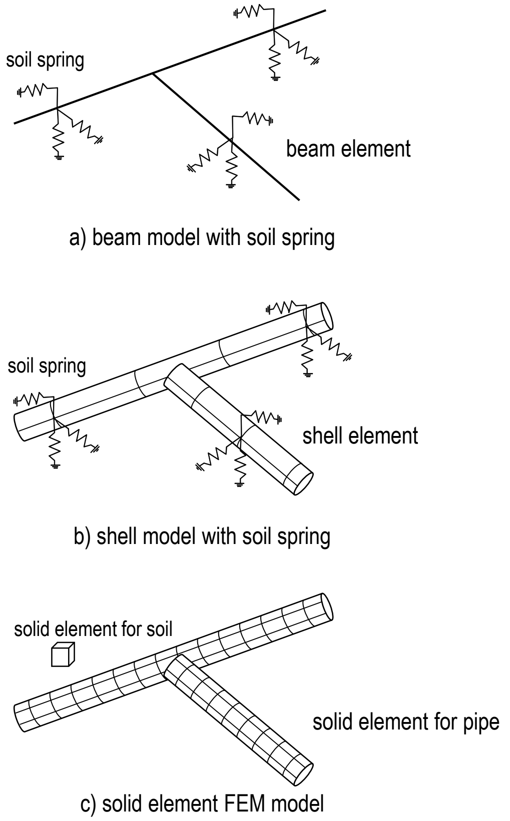


Fig. 8 Meta-modeling of pipeline network and embedded soil.

Table 3. Use of different models for IES_PN

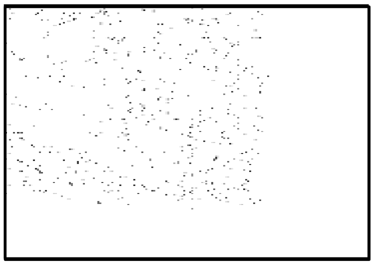
	model	pipe	soil
entire network	beam	beam	soil spring
damaged part	shell model	Shell	soil spring
detail of damaged part	solid element	solid	solid

As an example, data extraction is made for a pipeline network in the area of 54 km^2, and information is stored as a CMD of Network. Black-and-white images of 1 m resolution are made, and the number of different pixels is 2,191 for the image of 8,810 x 6,376 pixels. In Fig. 9, the original data set, the converted CMD and the difference of the two images are presented. It turns out that the difference of 0.0039 % is due to antialiasing in making the images, and all the data is successfully extracted.

According to the meta-modeling concept, we construct a beam model for the seismic response analysis of the entire model, using Network. When there are parts of the network which need more accurate analysis, we construct a shell or solid element FEM model. Soil-structure interaction is modeled as a soil spring in the beam model and the shell element FEM model, but solid elements are used for the surrounding soil in the solid FEM model.

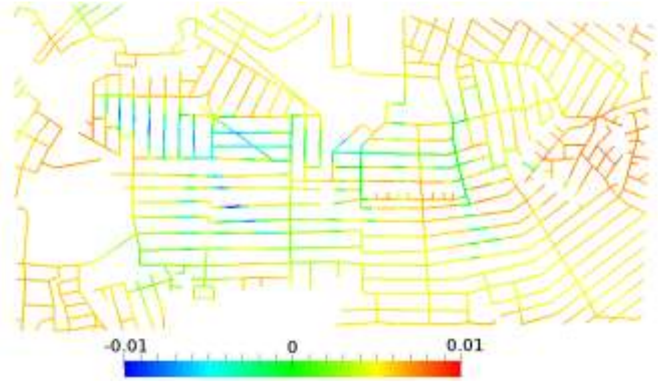
a) original data set

b) converted CMD

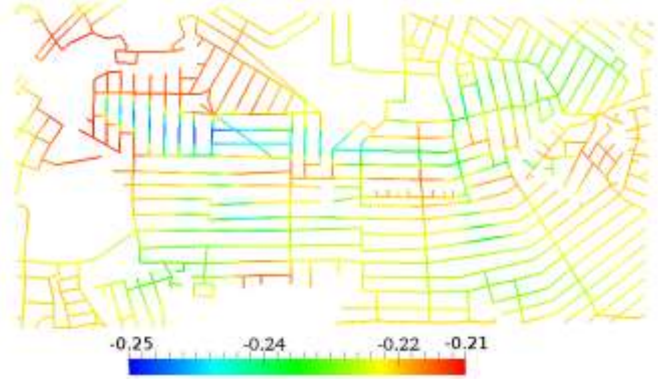


c) difference in BMP

Fig. 9 Errors in converting original data set.



a) uniaxial displacement along pipe direction



b) uniaxial strain along pipe direction

Fig. 10 Results of beam model.

The automated construction of the beam model from Network is not difficult, since it readily gives L of Eq. (8). Major tasks in the construction are to split each pipe to small segments which are modeled as one beam element, and to ensure the proper connectivity for the connected pipes at a junction. The properties of the beam element is readily determined from the three properties of the pipe, namely, diameter, thickness, and Young's modulus. Three soil springs are attached to each node of a beam element, one for the axial direction and two for the transverse directions. The properties of the axial spring and the transverse spring are determined according to a seismic design code of pipeline; bi-linear relation is used as the relation between the force transmitted from the soil to pipe and the relative displacement of the pipe with respect to the soil.

In Fig. 10, an example of the results which are obtained by using the beam element is presented; a) and b) are for the displacement component along the pipe direction and normal strain component in the pipe direction, respectively. Input ground motion is given by using the ground motion analysis presented in the preceding subsection. We do not reach a stage of validating these results, even though they do not seem intuitively wrong.

The automated construction of the shell model is essentially the same as that of the beam model, except for the junction to which two or more pipes are connected. This is because the data about the pipe configuration stored in the original GIS is the polyline data of the network and the diameter and thickness of each pipe. We have to interpret the data to capture S of Eq. (9), which is the shell middle plane. The configuration of the junction is especially complicated; it is not trivial since commercial mesh generation software fails to accurately calculate an intersecting curve at the intersection of two tubes. Modeling a simple T-junction of pipes with equal radii requires a skillful modeler to subdivide the surfaces and use his geometric knowledge. We thus develop a code with several templates for automatically generating surface models of commonly occurring pipe junctions. For the surface geometry model, we used B-splines due to two advantages. The first advantage is that a B-spline geometry model can be directly used for analysis; even it is used for Iso-geometric analysis [11, 12], which does not require mesh generation and is readily analyzed by using commercial software. The second advantage is that most of mesh generators or CAD software accept a B-spline geometry model. The generated surface model is saved in the standard format of IGES (Initial Graphics Exchange Specification), which is exchangeable among various software of CAD and FEM.

A solid element FEM model is constructed from the shell model, when most accurate seismic response analysis is needed. As mentioned, unlike the beam and shell element, this model uses solid elements for soil as well. Non-linear plasticity of the surrounding ought to be used in the solid element FEM model. However, the most critical feature is the treatment of the interface condition between the pipe and the soil; slip on the interface would be accepted to some extent, even though suitable traction is transmitted from the soil to the pipe. Since the interface conditions are not fully clarified, we do not have any other choice of employing the perfect bonding conditions, assuming that the non-linear plasticity of the soil solid element is able to reproduce both slip and traction transmission.

In Fig. 11, presented are the shell model and the solid element FEM model for the junction part; recall that the shell model have soil springs at all its nodes and the solid element FEM model is surrounded by solid elements of the surrounding soil. The junction is located at the left side of the network and has the smallest normal strain; see Fig. 10b). The strain distribution for these two models subjected to the same ground motion is computed and displayed in Fig. 12; the absolute value of the normal strain is plotted in this figure. As is seen, there are some discrepancy between these two models, mainly because the difference in treating the soil-structure interaction effects. Like the case of the beam model, we have not validated these results of the two models. These results are regarded as merely demonstration of IES_PN.

C. *Seamless Simulation of IES_PN*

The previous two subsections are for the first two of the three processes of earthquake hazard and disaster. Coupling of the two processes is one-way, i.e., from the earthquake wave propagation process to the structural seismic response process, not vice versa. In IES_PN, the ground motion analysis of the surface ground layers outputs the time series of strain distribution along the pipeline, which is given a set of displacement time series at many nodes of the pipeline. This output becomes input of the seismic response analysis of the pipeline network.

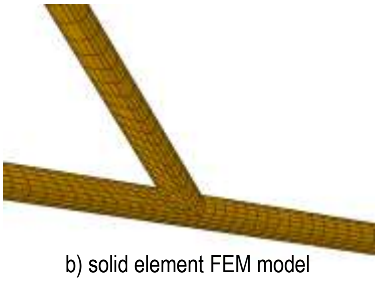
At this moment, coupling is not made automatically. Manual operations are needed to convert the ground motion analysis output to the seismic response analysis input. This is because the results of the ground motion analysis which covers a whole urban area has to be converted to a set of one-dimensional distribution along each pipe of the network.

While more smooth coupling is surely needed to achieve seamless simulation between the earthquake wave propagation process and the seismic structural response process, IES_PN needs a module for the preparing and recovering process. This last module is essential to develop an alternative of the present earthquake damage assessment method that is based on empirical equations.

We have developed a prototype of this module, which, unlike physical process simulation of the ground motion analysis and the seismic response analysis presented, is a non-physical process simulation [13]. The developed module is based on multi agent simulation (MAS) [14, 15].

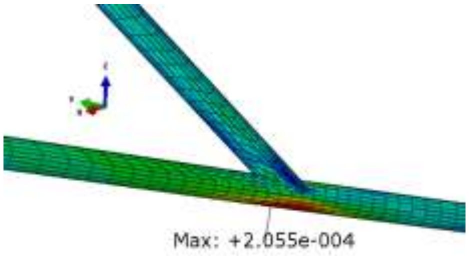
As a nature of non-physical simulation, it is a challenging task to make verification and validation for this MAS; no theory is established for repairing processes of pipeline networks damaged by earthquakes. MAS which is being developed is aimed at solving a well-posed mathematical problem, called a resource allocation problem. This problem is highly non-linear and discretized as it uses numerous non-linear and non-smooth functions and is difficult to be solved by applying ordinary numerical methods. Appendix presents detailed of the developed MAS.

a) shell element model

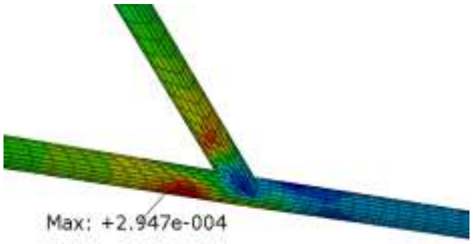


b) solid element FEM model

Fig. 11 Model details of connecting part.



a) shell element model



b) solid element FEM model

Fig. 12 Strain distribution of connecting part.

VI. Concluding Remarks

This paper presents the framework of IES_PN, which is being developed as a special system of IES. The core modules of IES_PN are the ground motion analysis and the seismic response analysis, and the analysis model and method are specially developed. Although not validated, trial simulations are made by using a prototype of IES_PN.

A major task which is needed to complete IES_PN is to couple the two developed method to a simulation of the repairing and recovering process. MAS for repairing process analysis is being developed, and is going to be coupled with the seismic response analysis.

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Appendix. Repairing Process Analysis

MAS is used in IES as analysis methods for repairing and recovering process [16, 17, 18, 19, 20]. The use of MAS for the repairing process analysis is new, as far as the authors have surveyed in the literature. In this section, we first pose a resource allocation problem for the recovering process [21, 22]. Then, we present MAS as a numerical analysis method of numerically solving this problem.

A. Resource Allocation Problem

A resource allocation problem is an optimization problem; to find the best way to allocate various resources in various place and time, so that a certain objective function is maximized. As for the repairing process of a pipeline network, an objective function is benefit of all users who do some activities using the network; the value of the network should be measured in terms of such users’ activities. The capacity of the network is reduced due to damages induced by seismic response, and engineers are dispatched to fix the damages. The way of assigning engineers to damage pipes is thus regarded as the resource allocation. Note that in this setting, the pipe damage is quantified in terms of the amount of resources, such as material, labor or energy, which are needed to fix it, and that engineer’s repair work is quantified as the speed of providing the resources.

To pose a resource allocation problem for the repairing process, we consider a network, users and engineers, and denote by b, c and d the benefit, the capacity and the damage, respectively. The following three basic assumptions are made:

1. a user contributes b, utilizing a network,
2. an engineer decreases d, repairing a damaged part,
3. a network increases c as d decreases.

The remaining task of posing the resource allocation problem is to give explicit relations to these assumptions.

As for the users, we consider a user has several activities, each of which contributes b. That is, denoting u^{nk} by the amount of using the network for the k-th activity of the n-th user, we have

$$b = \sum_{n,k} H^{nk}(u^{nk}), \tag{A1}$$

where H^{nk} is a function which converts the amount of the activity to the benefit? The capacity of the network, c, is a restriction to the sum of the users' activities, $\{u^{nk}\}$,

$$c > \sum_{n,k} u^{nk}. \tag{A2}$$

This c is determined later.

As for the engineers, we first denote by $\boldsymbol{W}^{ai}$ a set of resources which are required for the a–th task to repair the i –th damaged part of the network; $a = 1$, 2 or 3 indicates investigation, design, or construction work, respectively. Thus, $\{\boldsymbol{W}^{1i}, \boldsymbol{W}^{2i}, \boldsymbol{W}^{3i}\}$ is a set of resources to fully repair the i –th damaged part. We then denote by $\boldsymbol{s}^{ma}$ the work done by the m–th engineer per day for the a–th task, so that the accumulated work for the a–th task of the i –th damage, denoted by $\boldsymbol{w}^{ai}$, is updated by adding $\boldsymbol{s}^{ma}$. The engineer keeps working until

$$\boldsymbol{w}^{ai} \geq \boldsymbol{W}^{ai} \tag{A3}$$

holds, where the inequality between the vectors ($\boldsymbol{w}^{ai}$ and $\boldsymbol{W}^{ai}$) means all the components of the vectors satisfy the same inequalities. Note that $\boldsymbol{s}^{ma}$ is an index of the engineer's ability; a better engineer has larger $\boldsymbol{s}^{ma}$.

Finally, the capacity of the network is determined by a function G, as

$$c = G(\max_i d^i), \tag{A4}$$

where d^i is the damage level of the i–th damage; d^i is determined by the accumulated work, $\boldsymbol{w}^{ai}$, i.e.,

$$d^i = F^i(\boldsymbol{w}^{ai}, a). \tag{A5}$$

As is seen, the maximum value of d^i is used for the function G, since it gives the capacity of the network which is restricted by the most damaged part.

Now, using Eqs. (A1)~(A5), we can pose the resource allocation as "maximize b of Eq. (1) by suitably allocating engineers to repair damaged part of the pipeline network." A condition of Eq. (A2) is set for $\{u^{nk}\}$ by using c which increases as d^i's decrease when $\boldsymbol{w}^{ai}$'s are increased by adding $\boldsymbol{s}^{ma}$ of the assigned engineer.

B. *MAS for Resource Allocation Problem*

As mentioned, it is MAS that is used as a numerical analysis method to solve the above posed resource allocation problem. In general, MAS has two major elements, agents and environment. MAS for the resource allocation problem has two classes of agents, one for the users and the other for engineers, denoted by User and Engineer. There are a few User's with large u^{nk} or many User's with small u^{nk}, which corresponds to a manufacture or residents, respectively. Each Engineer could have its own value of $\boldsymbol{s}^{ma}$, but, for simplicity, we assume that the value of $\boldsymbol{s}^{ma}$ is common.

The environment of MAS for the resource allocation problem is a model of the pipeline network. It is a source from which User obtains benefit and Engineer repair damaged parts. It is therefore possible to construct the pipeline network model, based on the results of the seismic response analysis. The damaged parts of the model are synthesized by describing suitable $\{\boldsymbol{W}^{1i}, \boldsymbol{W}^{2i}, \boldsymbol{W}^{3i}\}$ in view of the level of the physical damage. In the environment of the pipeline network model, User's are fixed to use specific parts of the model, while Engineer's are daily dispatched to a damaged part.

In MAS for the resource allocation problem, the three functions, $\{F^i, G, H^{nk}\}$, which are used in formulating the problem, must be explicitly given. It is certainly true that even though there are relations between the arguments and the values of them, determining these functions from the available data is difficult. However, even simple approximated functions are sufficient to make a repair plan for the entire pipeline network in an urban area, which involves engineers of order of 1,000 per day for the sake of users of order of 10,000 or 100,000. A simple step function which gives a common value when its argument belongs to a certain range or a domain change its value is thus employed; for instance, $F^i$is given as

$$F^i(\boldsymbol{w}^{ai}, a) = \begin{cases} 0 & a = 3 \;\&\; \boldsymbol{w}^{3i} \geq \boldsymbol{W}^{3i}, \\ 1 & else. \end{cases} \tag{A6}$$

Here, for simplicity, it is assumed that the damage level is either 0 or 1, which corresponds to on and off the network service, respectively.

The daily allocation of the engineers to the damaged part of the pipeline network serves as a control variable of the resource allocation problem. In MAS, we introduce tactics in the following form:

$$S^i = (\,\boldsymbol{s}^{ma}, \boldsymbol{w}^{ai}). \tag{A7}$$

This form means that we allocate the m–th Engineer to the the a–th task of the i –th damage; it includes a case when no Engineer is assigned to the task. A set of is S^i called tactics and denoted by S, which is an explicitly described control variable of MAS for the resource allocation problem. Note that S or S^i changes daily.