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Automated Model Construction for Seismic Disaster Assessment of Pipeline Network in Wide Urban Area

Hideyuki O-tani, Muneo Hori and Lalith Wijerathne

Abstract

This chapter is on rational seismic damage assessment over a wide area through the development of a module for the automated model construction of a pipeline network of lifelines using geographic information system (GIS) data. The module is assigned a functionality that can generate a simple one-dimensional line model and a two-dimensional surface model with high fidelity for the pipe shape. The source code of the module is written in object-oriented programming in order to make it easier to extend it to generate other analysis models. The module was applied to the actual GIS, and the shape of the output model was verified. Numerical analysis was performed on the output of the module, and it showed that the automatically constructed model is mechanically valid and can be used for seismic response analysis.

Keywords: automated model construction, seismic disaster assessment, pipeline network, GIS data, object-oriented programming

1. Introduction

The importance of securing the high seismic performance of the pipeline network of lifelines [1] such as water and sewerage, electricity, gas, and communication needs no emphasis. The first step toward meeting this demand is the evaluation of seismic damage. Sheer size and the complex geometry of pipeline networks make it a challenging task to evaluate seismic damage assessment in urban areas. For instance, in a populated area spanning a few tens of square kilometers, the pipeline network may be several hundred kilometers long. Seismic damage at any one point in the pipeline network could affect the services in a large supply

area. Therefore, the pipeline has to be assessed at each point and carrying out this assessment manually requires an enormous amount of labor.

Several types of pipes are used in lifelines and their design life is usually 50 years or more. Therefore, the pipeline network in any place of seismic damage assessment is composed of dissimilar pipes. The structure of the ground at a location, which influences the amplification of seismic motion, is far from uniform when viewed in the scale of the length of the entire city. This nonuniformity further complicates the point-by-point seismic damage assessment of lifelines.

It, therefore, becomes necessary to assess seismic damage over a wide area by relying on a *fragility curve* [2–5] the empirical relation between the damage ratio of the pipeline network and the strong ground motion index. The curve can be improved by analyzing the effect of the localized nature of the structure and the site, by utilizing actual damage data. However, such seismic damage assessment is clearly different from the seismic-resistant design [6–8] of newly laid pipes in which nonlinear finite element analysis was used by considering the coupled effect of the soil and the structure.

The seismic damage to the pipeline network of lifelines can be assessed in a fairly rational manner and with high accuracy using the seismic-resistant design method. While the design is made only for a part of the pipeline network, assessment has to be made for the entire pipeline network of the city that is being assessed for seismic damage. It is a challenging task to construct analysis models with equivalent fidelity of those used in seismic-resistant designs, for a large pipe network.

An analysis model is essential in order to achieve a fairly rational seismic damage assessment. It does not have to be a unique or exclusive model. In the seismic damage assessment of lifelines, for instance, it would be more convenient to choose from a variety of analysis models ranging from a simple beam model to a sophisticated shell element model, which may be used according to the accuracy required for evaluation. With this objective in mind, we have aimed at developing a module that will convert the data of the pipeline network of lifelines into analysis models for the assessment of various types of seismic damage. As explained in Section 2, data on the pipeline network are available from some GIS records. The basic feature of this module is its high degree of robustness, that is, the possibility of constructing an inappropriate model is minimal.

The contents of this chapter can be summarized as follows. The module for converting data into an analysis model is described in Section 2, together with the data conversion methodology and a detailed description of the data structure of the module. Verification of the module is carried out in Section 3. In Section 4, as an illustrative example, seismic disaster assessment is conducted for a pipeline network and its connections. Section 5 gives the conclusion about the developed module.

2. Model construction module

In this section, we describe the module that converts the data recorded in the GIS into an analysis model of the pipeline network. As already mentioned, there are several options available

for analysis models with varying degrees of complexity. In order to simplify the software maintenance of the module, the data recorded in the GIS are first converted to "model data." Model data refer to the essential information for the construction of the analysis model extracted from GIS, and the conversion into a specific analysis model is done by integrating the model data. The model construction module is composed of two submodules: the "GIS data conversion submodule" and the "model data conversion submodule" (**Figure 1**). Dividing the module into two submodules through the model data prevents the modifications made on one submodule from affecting the other submodule.

2.1. Source data

Six types of lifelines are considered in this study: water supply, sewage, gas, electricity, communication, and road networks. GIS created under a standard protocol is available for these six types. The GIS protocol is systematic but complex. Basically, data are recorded in a binary format in which records consisting of a fixed length header part and an undefined length content part are arranged in order; the byte order of the data constituting the header part and the content part is different for each data type. The main information of each record is compiled in **Figure 2**.

The contents of the record are divided into a shape record, in which shapes such as polylines and polygons are recorded; and an attribute record that records material properties and information such as pipeline radius, whether it refers to the inner or outer diameter, pipeline
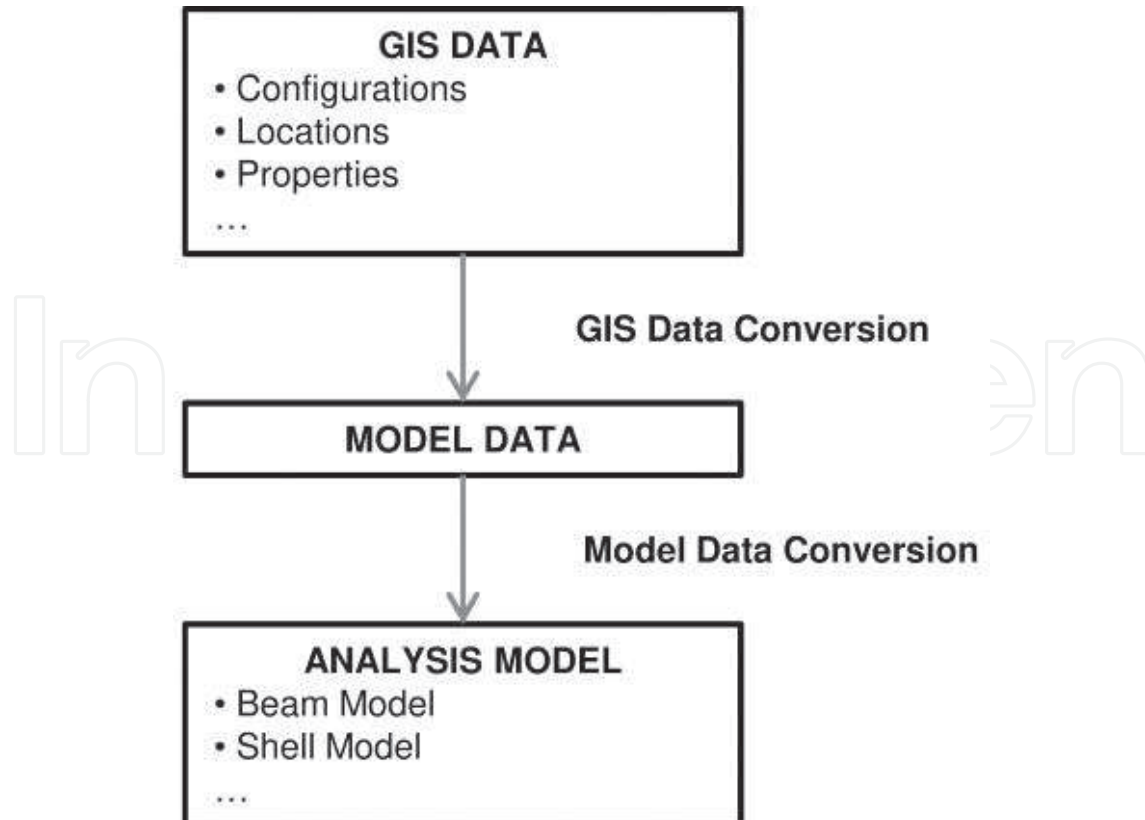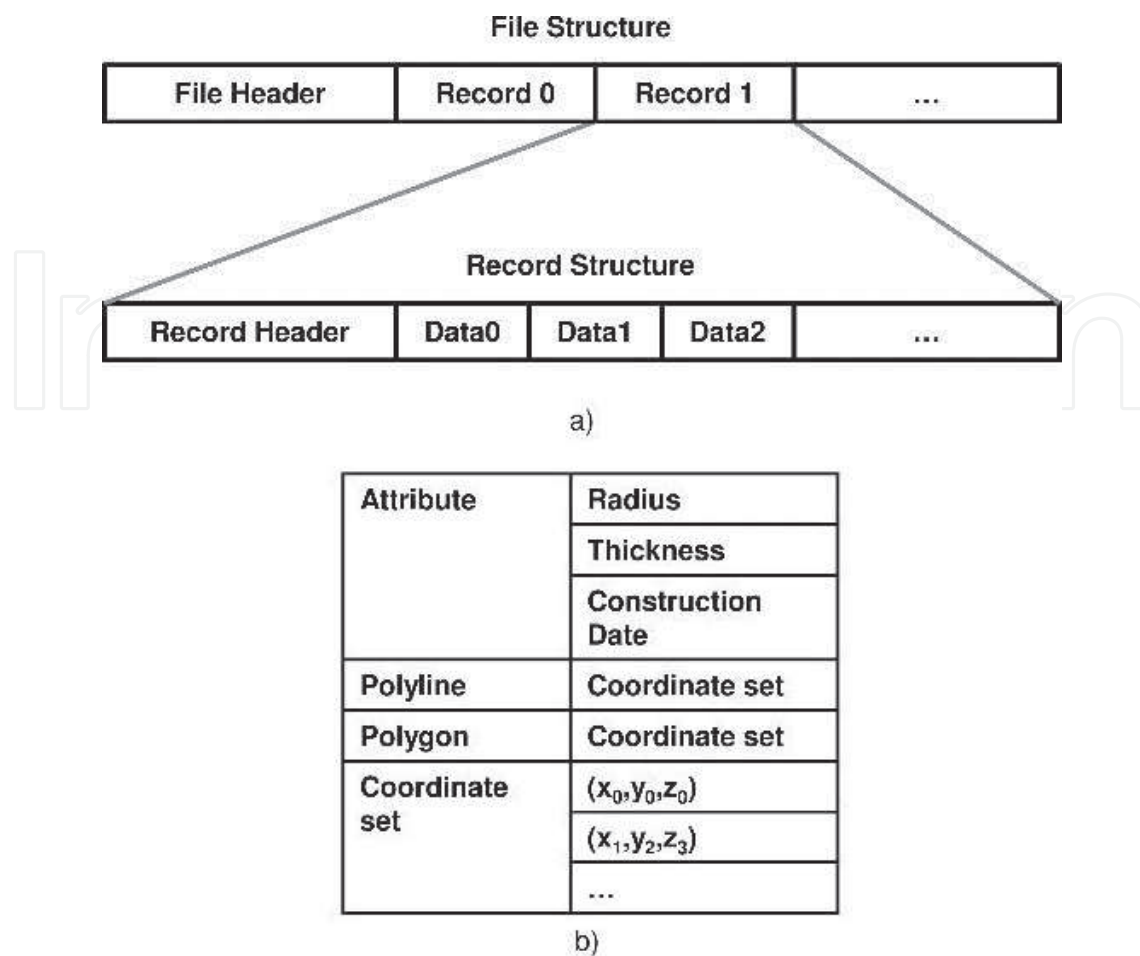

**Figure 1.** Schematic view of data conversion.

File Structure

File Header	Record 0	Record 1	...

Record Structure

Record Header	Data0	Data1	Data2	...

a)

Attribute	Radius
	Thickness
	Construction Date
Polyline	Coordinate set
Polygon	Coordinate set
Coordinate set	(x_0, y_0, z_0)
	(x_1, y_2, z_3)
	...

b)

Figure 2. Overview of GIS consisting binary records. (a) Typical file structure in GIS; (b) example of record contents.

thickness, etc. The record representing the shape of the pipeline network is a polyline composed of a sequence of dots. Coordinates are assigned to each point, and successive coordinates indicate the connections in the polyline. Thus, the shape of a network with branches is configured as a set of polylines. These two types of records are necessary to construct an analysis model of the pipeline network.

It must be noted here that the GIS used in this study is based on a CAD protocol and the connection of successive points in the polyline is the only information about the connectivity of the network. Even if the result of visualizing the analytical model of the pipeline appears to be satisfactory, constructing an analysis model merely by connecting these points will not be sufficient. More sophisticated data conversion ensuring that the points are mechanically connected is needed. Visualization of the connection of points is a necessary but an insufficient condition. It is believed that analysis is necessary in order to verify whether the points are connected in a manner so as to function as a pipeline network.

2.2. GIS data conversion submodule

The GIS data conversion submodule converts the GIS data into model data that can be used to construct various analysis models of the pipeline network. The model data are a set
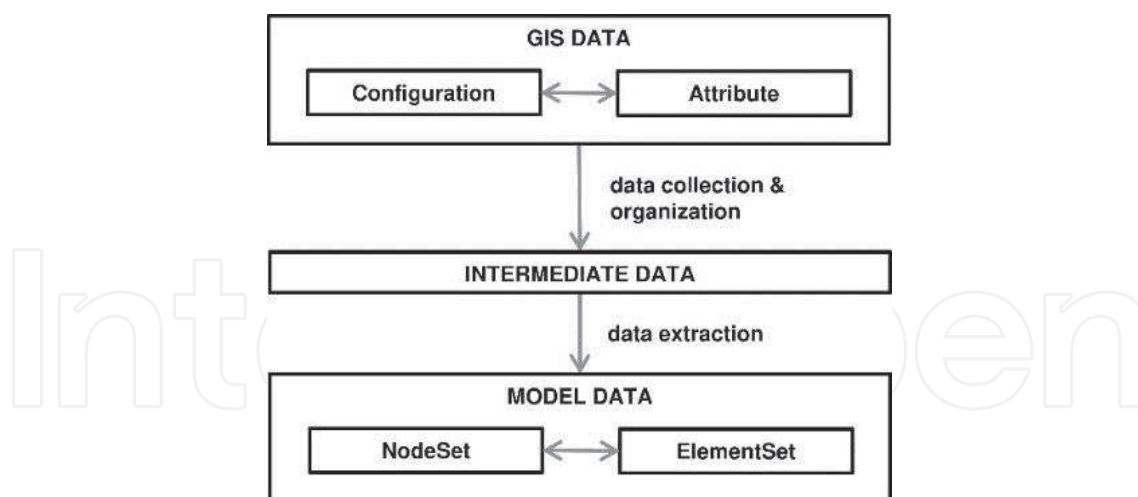
Figure 3. Main functionalities of GIS data conversion submodule.

of shape records and attribute records of the pipeline network distributed and recorded in the GIS into a single dataset. It provides a clearer description of the connectivity of pipelines than the original GIS, in order to facilitate its use as a common information source for constructing analysis models. The main functions of this submodule are to read the entries in the GIS record, extract the data necessary for the construction of the analysis model from the record, and register the extracted data as model data. These functions are summarized in **Figure 3**.

The GIS for all the six lifelines have a common protocol and share important features of the records, but the GIS of each lifeline contains its own specifications in the record details. Object-oriented programming (OOP) [1, 9] is therefore effective in creating the code of the GIS data conversion submodule. Inheritance, polymorphism, and template functions are the advantages of using OOP to handle the key functions shown in **Figure 3**. In the hierarchical structure shown in **Figure 4**, virtual classes are created as common items and concrete classes for each of the actual lifelines are created on the basis of the virtual classes. Thus, the model data conversion submodules for GIS of all the lifelines have the same appearance.

The only items common to the GIS records for all the six kinds of lifelines are the records of the polylines representing the shapes of the networks; the other items being different for each lifeline. Therefore, a common container object is created for the polyline records and separate container objects for other records. Further, an object to associate with the two kinds of objects is created in order to build an analysis model of the network using the two kinds of objects.

The following four objects are created for the container of the polyline records: NodeSet, ElementSet, Network and NetworkSet. NodeSet is a container object for the point coordinates, and the connectivity of the points is contained in ElemenSet. Network is a pair of NodeSet and ElementSet, and NetworkSet is a set of Network.

- NodeSet is a set of Node, and an entity of Node corresponds to a node in the network. Each Node entity is constructed from the polyline records, and put into a NodeSet entity without duplication. NodeSet also contains the IDs for Node.

- ElementSet is a set of Element, and an entity of Element corresponds to a record of a polyline. Each Element entity is constructed from a polyline record as a series of Node IDs, and put into an ElementSet entity without duplication. Element also contains an entity of Attribute, which is a container object associated with the property of a pipeline.

- Network is a pair of NodeSet and ElementSet, and an entity of Network is constructed from one fragmented file in GIS. Network corresponds to a part of the target pipeline network.

- NetworkSet is a set of Network, and an entity of NetworkSet corresponds to an entire pipeline network.

Figure 5 shows the construction flow of a NetworkSet entity; Segment is a straight line specified by the neighboring point coordinates in a polyline record.

2.3. Model data conversion submodule

The role of the model data conversion submodule is to construct an analysis model from model data and create input files for the program that performs the analysis using this analysis model. In this study, a model data conversion submodule that creates 1D line models and 2D surface models is presented.
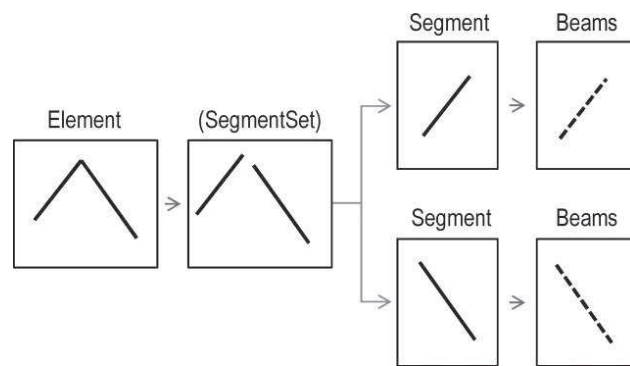
2.3.1. 1D line model

1D line model is an assembly of beam elements constructed from an entity of NetworkSet, which is a model data that corresponds to an entire pipeline network. Beam elements are created by dividing an entity of Segment, which corresponds to two neighboring points in a polyline record into linear fragments of equal size. Consequently, the process of creating a 1D line model is, in contrast to the conversion process of GIS data conversion submodule shown in **Figure 5**, a process that decomposes an entity of NeworkSet into beam elements. **Figure 6** shows the decomposition process.
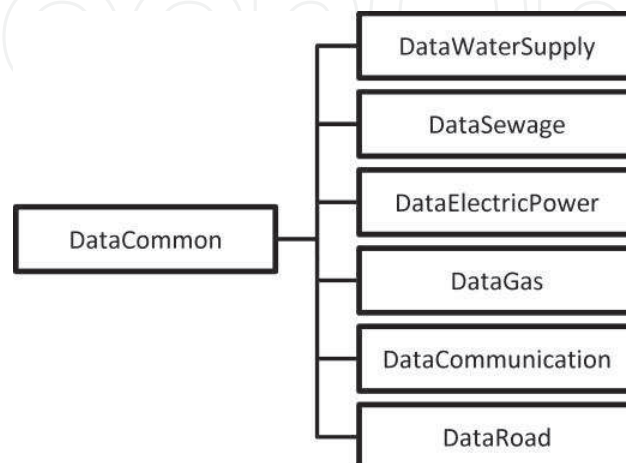
Figure 4. Data hierarchy of GIS.
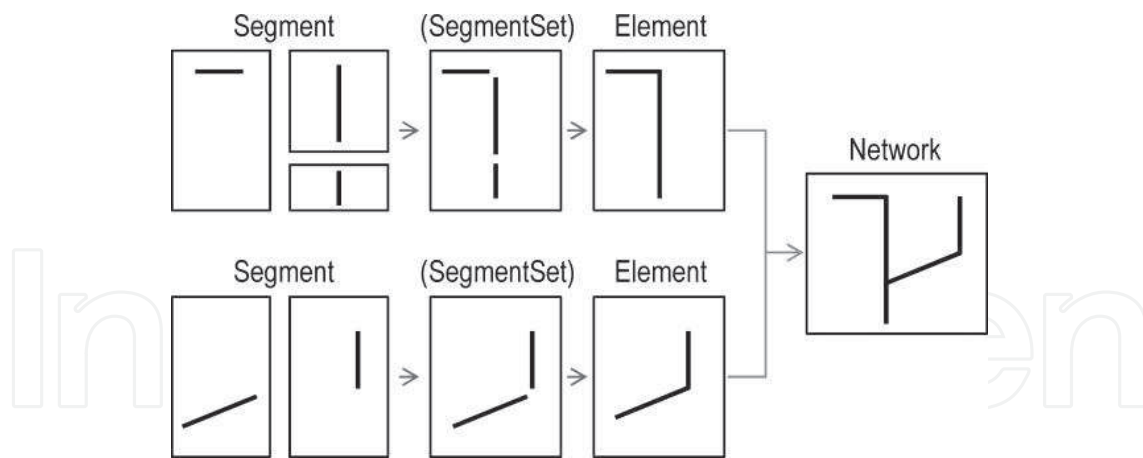
**Figure 5.** Flow of converting GIS to NetworkSet.

Figure 6. Decomposition flow of model data to beam elements.

It is possible to increase the transparency of the conversion process by using the same object as the model data as the container object for the 1D line model. However, to achieve high transparency, it is important that at the same time the container object has a simple structure. Therefore, the following three structures are considered as candidates for the structure of the container object of the 1D line model.

- A Beam object is created as the container object of the beam elements. Furthermore, a PipeSegment object is created as the container object to assemble the beams created from the same Segment entity. PipeSegment corresponds to Segment of the model data. In this case, the depth of the structure of the container object of the 1D line model is 5 (**Figure 7a**)).

- Without holding information about PipeSegment, as necessary, Segment is divided by creating an entity of PipeSegment. In this case, the depth of the structure of the container object of the 1D line model is 3 (**Figure 7b**)).

- The entire 1D line model is adapted to an entity of Network. In this case, the depth of the structure of the container object is 2 (**Figure 7c**)).

The first candidate features a highly transparent conversion process. Its structure is the structure of model data supplemented with the container object of the beam elements. However,
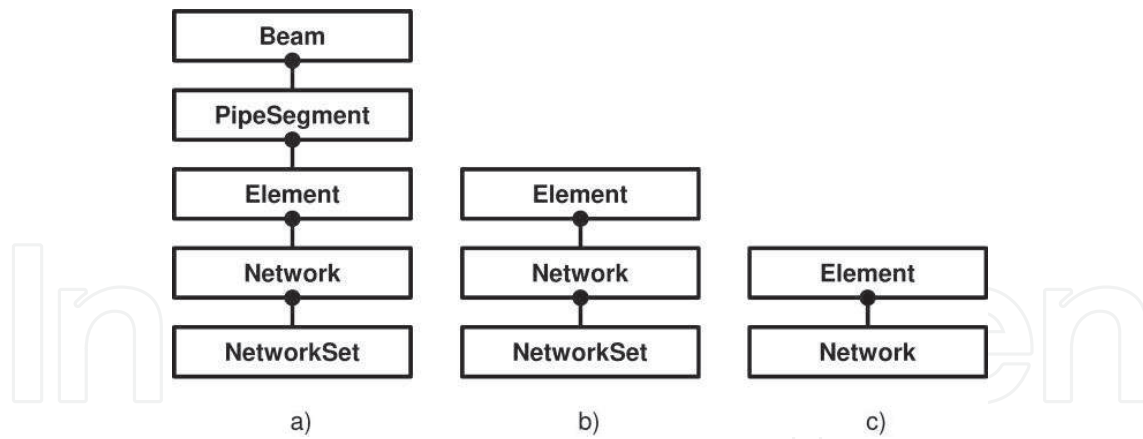
Figure 7. Candidates of layer structure for 1D line model. (a) Five layer structure; (b) three layer structure; (c) two layer structure.

the depth of its structure corresponds to 5 and it is large; therefore, its ultimate transparency is harmed. Regarding the second candidate, considering the characteristics of PipeSegment, namely that PipeSegment can be simply created by dividing Segment into the assigned number of beam elements, the number of divisions of the beam elements are allotted for each Segment. As a result, it is possible to create the necessary beam elements instead of maintaining information about the PipeSegment throughout the pipeline network. This achieves significant memory savings and simplifies the structure of the container of the 1D line model. Considering the third candidate, the structure of the container is even simpler and is premised on collectively modeling the entire pipeline network. However, it is not necessarily essential to model the entire pipeline network recorded in the GIS data. Therefore, this structure wastes memory. As stated earlier, the second candidate, or in other words, the candidate with a depth of 3 is suitable as the structure of the container of the 1D line model. Nonetheless, the names of each container are revised considering that details such as the number of divisions applied to Segment differ from the model data. **Figure 8** shows the three-layer structure of the 1D line model along with the three-level structure of the model data.

2.3.2. 2D surface model

A 2D shell model is created only for parts with conspicuous damage specified by a 1D line model. In almost all cases, locations of conspicuous damage are the junctions on pipes. The shape of the
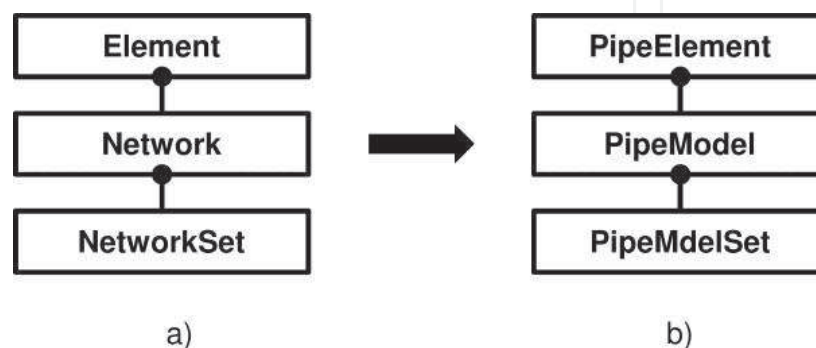

Figure 8. Three-layer structure of 1D line model together with corresponding three-layer structure of model data. (a) Model data; (b) 1D line model.

model is created based on the Non-Uniform Rational B-Spline (NURBS) surface. One merit of the NURBS surface is that it can be directly applied to isogeometric analysis that does not require mesh division. The model constructed is saved in the Initial Graphics Exchange Specification (IGES) format, which is a form that enables conversion between various CAD systems and a form that can be used by almost all finite element method (FEM) software packages. The analysis using a 2D shell model is executed based on an isogeometric analysis program or a standard FEM program.

It is straightforward to create a linear cylinder-shaped 2D surface model adapted to a beam element based on a NURBS surface. However, a junction on a pipe, the part where surfaces intersect, is not necessarily strictly represented by a NURBS curve. It may require to be approximated by a B-Spline curve.
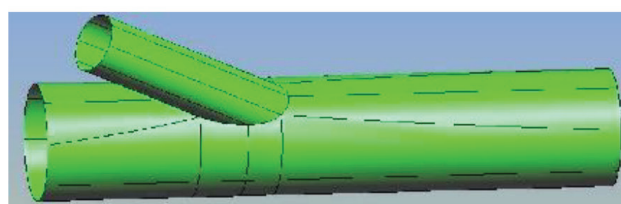
On an actual pipeline network, there are junctions of many different kinds; however, in this study, the shape of the junction is created as the intersection of two pipes. As a result, the
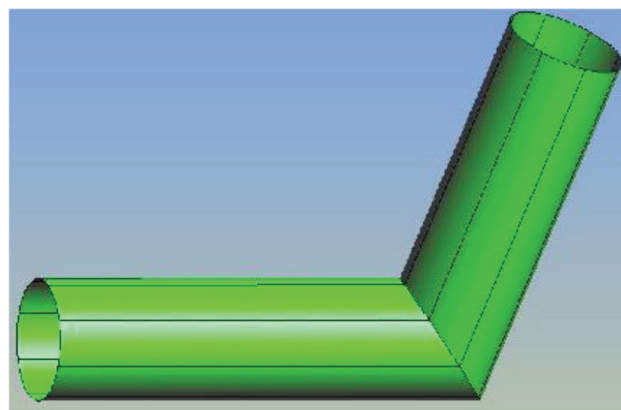
a)
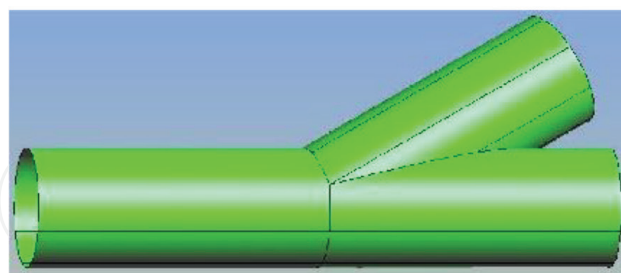
b)

c)

Figure 9. Three types of junctions studied in this chapter: (a) elbow, (b) T-junction of equal-radius-tubes, and (c) T-junction of unequal-radius-tubes.

shapes of the junctions are the three shown in **Figure 9**, namely elbow junctions, T-junctions of pipes with equal diameters, and T-junctions of pipes with unequal diameters. Following the method of Global Curve Interpolation, the elbow junctions, and T-junctions of pipes with equal diameters can be handled as belonging to the same group.

3. Examples of constructed model

This section presents some verification tests which were conducted to ensure the correctness of the developed module for automated model construction. The target large lifelines networks in metropolis like Tokyo consist of a very large number of components and have complex configurations. The objective of these verification tests is to ensure that the developed model constructor is equipped with all the necessary logic to cope with all the complexities in lifeline networks of large metropolis.

3.1. 1D line model

The objective of the first verification test is to ensure that the developed module has necessary logics to cope with the complexities in large network. The network shown in **Figure 10a**, an actual network with spatial extents of 8.66×6.3 km^2, was used in this verification test; location and type of the network is not mentioned for security reasons.

Figure 10b shows the configuration of the data extracted by the automated model constructor. Though **Figure 10a** and **b** is visually identical, detailed comparisons are necessary to ensure the correctness of the extracted data. It is not possible to make a one-to-one comparison of the original GIS data and the extracted data; the extracted data are stored in a different format which is analysis friendly, and redundancies included in GIS data are eliminated. High resolution (8810×6376 pixels) images of both the GIS and extracted data were compared to check the accuracy. Out of the 56,172,560 pixels, only a scattered set of 2191 pixels were found to be different. To make more quantitative comparison, we defined the error index, which was estimated to be 0.0039%.

$$E = \frac{\text{Number of different pixels}}{\text{Number of pixels}}, \tag{1}$$

Further investigations indicated that these negligible differences were due to due to the anti-aliasing effects in image generation, confirming that all the elements were correctly extracted. This comparison confirmed that the developed submodule was able to construct a 1D line model accurately.

3.2. 2D surface model

Accuracy of the T-junctions with unequal radii pipes is demonstrated in this section as one of verification for the data conversion submodule for the 2D surface model. In the case of junctions with equal radii pipes, the intersecting curves, which are ellipses, can be exactly modeled with NURBS or accurately approximated with B-splines. On the other hand, the

a)

b)

Figure 10. Comparison of 1D line model with original GIS. (a) Original GIS; (b) constructed 1D line model.

intersecting curves of T-junction with unequal radius cannot be exactly modeled with NURBS or B-splines and produce the highest error of approximation. Hence, the error of approximating such intersecting curve is considered in this verification.

A T-junction formed by pipes of radii 2 and 1 m, intersecting at 30° angle is considered in this verification test. The surface geometry was modeled as collection of eight bivariate B-splines of third order. Varying the number of control points for approximating each of eight segments, the point wise error $\sqrt{\sum_{k=1}^{3}(x_k^{app} - x_k^{ana})^2}$, where x^{app} and x^{ana} were points on the approximated and analytical curves, was estimated. **Table 1** shows the maximum normalized errors with 6, 8, 10, and 12 control points. As shown in **Figure 11**, these errors are highly localized, and maximum error relative to radius of the smallest pipe is only 0.08%. It is thus shown that the developed submodule can generate 2D surface model with sufficient accuracy. If required, the accuracy can be further improved by increasing the order of B-splines and/or number of control points.

Number of control points per curve segments	Maximum of pointwise error (mm)
6	5.6
8	2.4
10	1.3
12	0.8

Table 1. Maximum pointwise error in B-spline approximation with different degree B-spline.
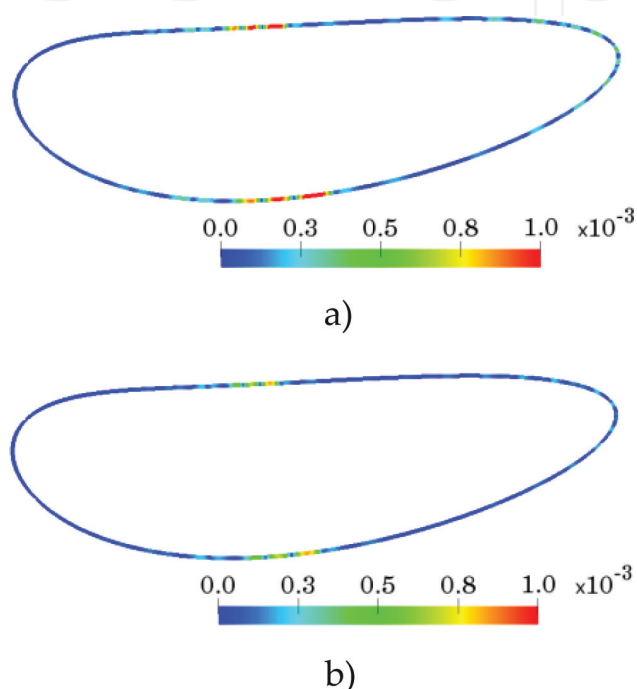
Figure 11. Distribution of error of approximation at 808 points on the intersecting curve of T-junction with 2 m and 1 m radii pipes. The intersecting curves are approximated as a collection of 8 B-spline curves, each with the given number of control points. (a) 10 control points per segment; (b) 12 control points per segment.

4. Examples of seismic response analysis

The main application of the extracted GIS data is seismic disaster assessment of buried lifeline networks. In this demonstrative analysis, small part of the network shown in **Figure 10a** subjected to a historical earthquake ground motion was analyzed to identify the damage locations. Though accuracy is high, seismic disaster assessment of an entire network with 2D analysis models is computationally expensive. Instead, first analyzing a computationally light beam element model to identify possible damage locations, and then using 2D models to analyze only the local links connected to those possible damage locations is a cost effective approach which does not sacrifice accuracy. The demonstrative examples presented in this section use this strategy to reduce computational cost.

| (a) Soil property	
Shear wave velocity (m/s)	190
Density (tf/m^3)	1.9
Shear modulus (tf/m^2)	0.47
Poisson's ratio	7000
(b) Pipe property	
Outer diameter (cm)	21.63
Inner diameter (cm)	20.47
Thickness	0.58
Cross section area (cm^2)	38.4
Young's modulus (kgf/cm^2)	2.1×10^6

Table 2. Material properties used in simulation.

We made use of a general purpose finite element package, ABAQUAS, in this analysis. The input data for ABAQUS were automatically generated by the developed modules. **Table 2** shows the material properties used in the analysis; some standard values were used due to confidentiality of data. Linear analysis was used for both the 1D and 2D analysis.
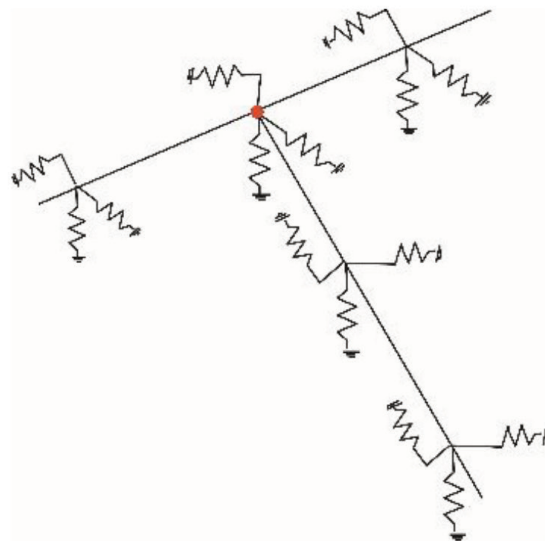
4.1. 1D line model

For the 1D linear analysis with ABAQUS, two-node pipe element PIPE31 was used to model the network, and the spring element SPRING1 was used to model soil-structure interactions (i.e., the reaction force produced by surrounding soil). To represent axial, vertical, and horizontal reaction forces, three springs were included at every node of the beam element model, as shown in **Figure 12a** and **b**.

Applying the respective components of the selected input ground motion at the free ends of each spring element, quasi-static analysis was conducted for each time record of the input ground motion. Only the major portions of input ground motion were used, since quasi-static analysis was employed. Samples of the input ground motion and the induced displacement are shown in **Figure 13**. The similarities in their trends indicate that there were no fatal mistakes in automatically generating the analysis model. In this analysis, we assumed the inertial contribution from the pipes was negligible compared to confinement of surrounding soil. It is straightforward to conduct dynamic analysis if the inertial forces are significant.

While there are several ways to assess the damage, we used the maximum strain due to bending and axial deformation of pipe elements to assess the damage (i.e., maximum strain exceeds a given critical value). As shown in **Figure 14**, the distribution of maximum strain was similar to that of bending moment. This indicated that bending action of pipes was the main contributor to the induced large strain. **Figure 15** shows close-up views of the two high strain regions which are indicated in **Figure 14**. **Figure 16** shows the identified damage locations based on the maximum strain criterion.
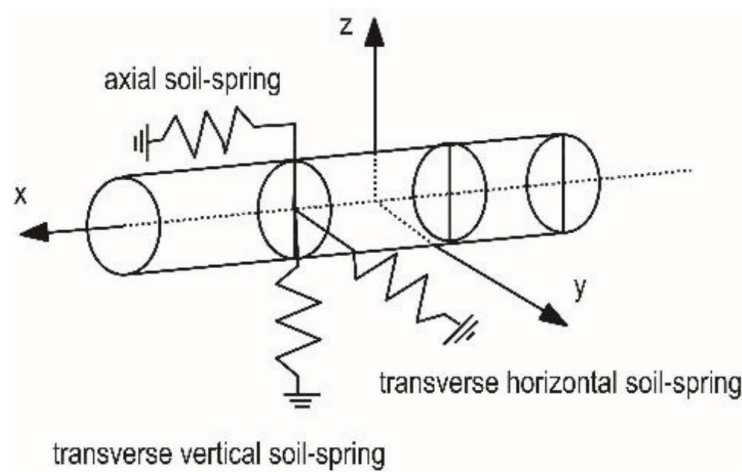
a)

b)

Figure 12. Soil-spring used in 1D line model: (a) shows three springs are attached to a pipe segment and (b) is a schematic view of a pipeline network attached with soil-springs.

4.2. 2D surface model for junction

Though lightweight in computation, the used beam element model mentioned earlier has a lower reliability in assessing damage states. Beam element models cannot accurately model stress concentrations at joins, hence the lower reliability. In order to increase the reliability, we model the damaged components, which are identified by abovementioned beam model, with shell elements, and the damaged status is decided based on the results of the analysis with shell elements.

We extended the data conversion submodule to automatically generate the required analysis shell element models for ABAQUS. First, the 2D B-spline surface model is generated for any pipe component identified according to the beam element analysis. Next, a mesh of sufficient spatial resolution is automatically generated based on B-spline data, and three springs are
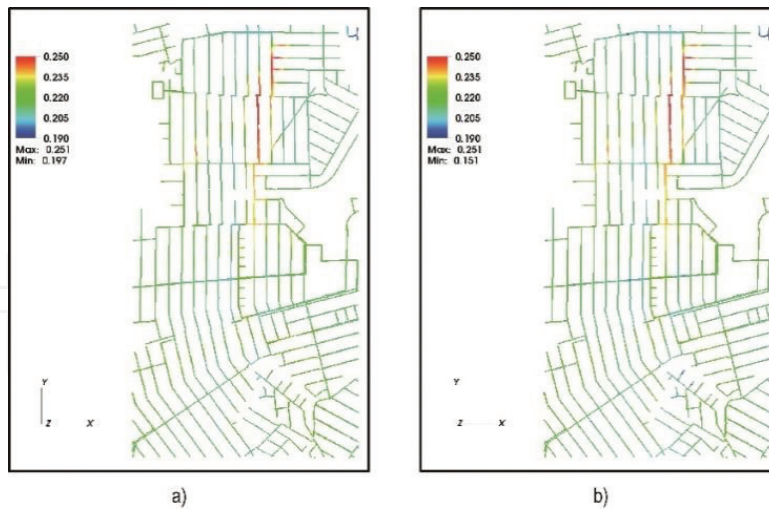
Figure 13. Displacement distribution in part of pipeline network. (a) Input displacement; (b) induced displacement on pipes.
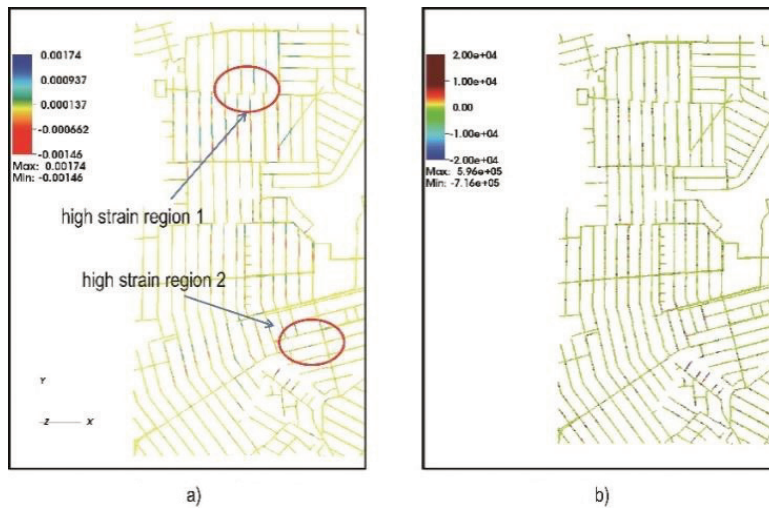

Figure 14. Distribution of strain and bending moment in part of pipeline network. (a) Normal strain; (b) bending moment.
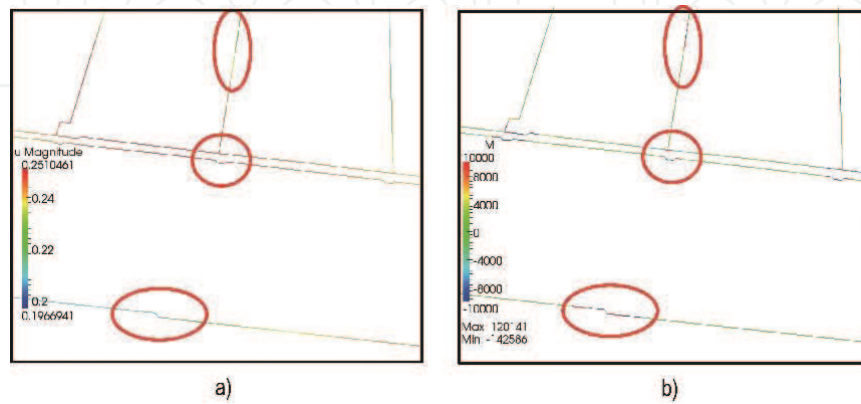

Figure 15. Close-up view of concentration of strain and bending moment in pipeline network. (a) Input displacement (m); (b) bending moment (Nm).
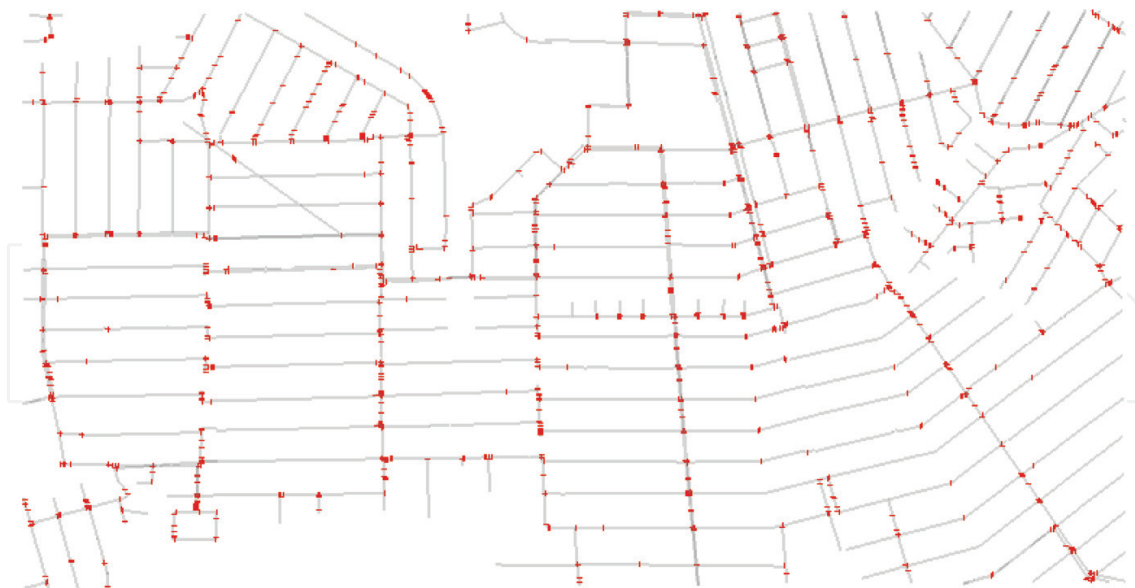
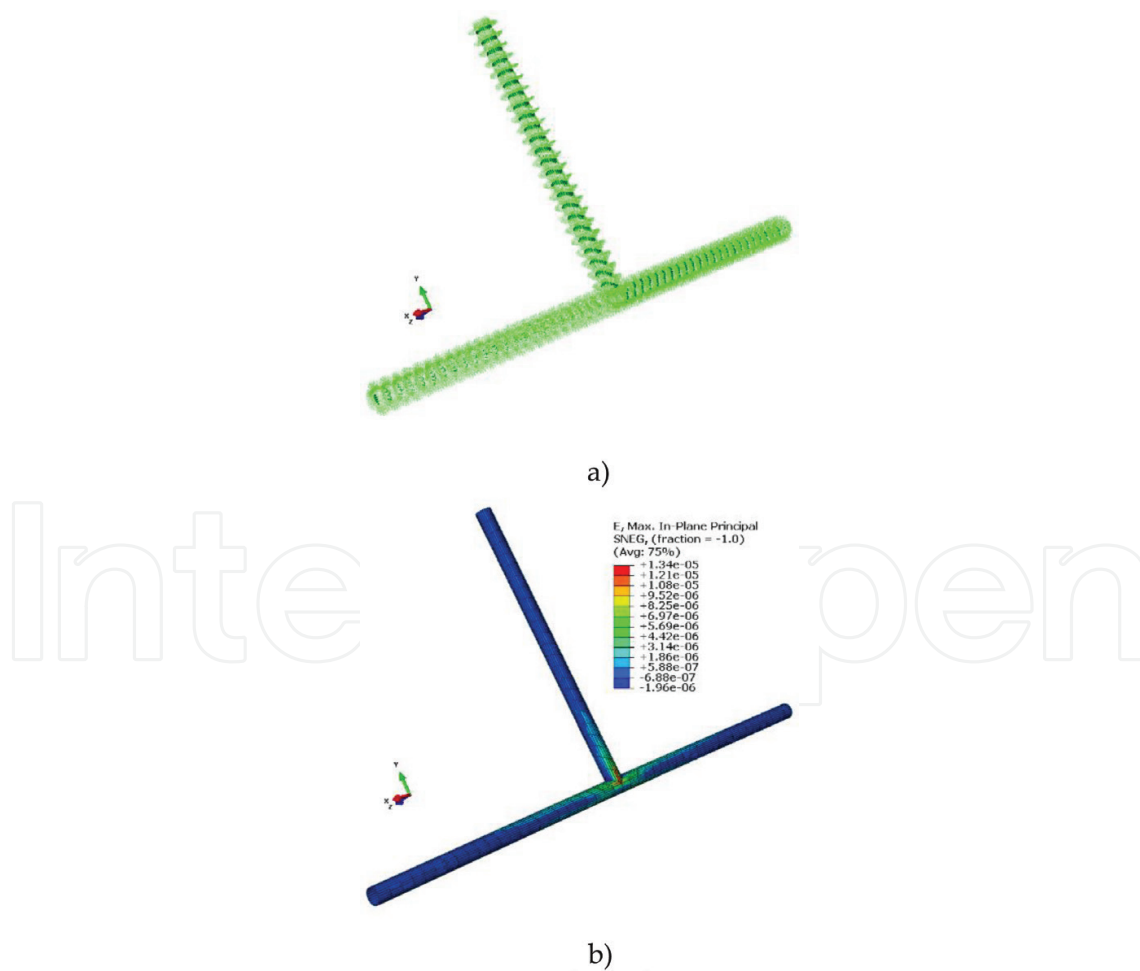**Figure 16.** Example of critical points in pipeline assessed by strain.

a)

b)

Figure 17. Automatically generate shell element analysis model is shown in (a). Three springs are attached to each node to represent surrounding soil. Distribution of the maximum in-plane strain is shown in (b).

attached to each node of the shell element model to represent the reaction of the surrounding soil. The three springs are oriented in axial, radial, and tangential direction at each node (see **Figure 17a**). The spring properties are assigned according to the properties of surrounding soil. The displacements at the free ends of the springs are assigned according to the ground motion data. Including all these information, the input file for ABAQUS is automatically generated. **Figure 17b** shows the distribution of the maximum principle strain. Based on the results of this analysis, the damage state at the junction is decided.

As demonstrated in this section, the developed automated model constructor makes it straightforward to assess seismic performance analysis of a pipe network. The whole process can be automated with batch scripts. Though only a small network is used in this demonstration, analyzing a large network is straightforward.

5. Concluding remarks

A module that automatically constructs an analysis model of a pipeline network by converting the GIS data of a lifeline was successfully developed. The module functions as designed without failing to read the GIS data or output the analysis model. GIS can be used to analyze the earthquake response of a lifeline, expanding its potential power.

Acknowledgements

Author details

Hideyuki O-tani[1]*, Muneo Hori[2] and Lalith Wijerathne[2]

*Address all correspondence to: h.o-tani@riken.jp

1 RIKEN Advanced Institute for Computational Science, Chuo-ku, Hyogo, Japan

2 Earthquake Research Institute, University of Tokyo, Tokyo, Japan

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