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(Citation)
IEEE/ASME Transactions on Mechatronics,26(6):2881-2887

(Issue Date)
2021-08-31

(Resource Type)
journal article

(Version)
Accepted Manuscript

Automatic Construction of Three-dimensional Ground Model by Data Processing

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***Abstract*— There have been attempts to improve the operational efficiency of construction projects and plan response countermeasures for estimated damage following disasters through the utilization of accumulated electronic data, which constructs a digital twin that can reproduce a physical space in cyberspace and feedback the cyberspace simulation results to physical space. However, the application of such simulations is limited, unless numerical models can be automatically constructed from the data. In this study, we develop a program that utilizes a data processing platform to read, transform, and integrate data to create mediated data with a common data structure. This mediated data can be used to construct analytical models for various numerical analyses. Using the program developed, a grid model of three-dimensional ground surface as the mediated data was constructed based on borehole data obtained through a ground survey. Each grid point has basic material parameters of soil, and these parameters are estimated from borehole data and other investigation reports. Each grid point has general geotechnical parameters and can be easily converted to a three-dimensional finite element model. When the borehole data is added or changed, the analytical model can be updated with almost no cost, whereas it would be very costly to create the model manually.**

***Index Terms*—Borehole Data, Data Processing Platform, Grid Ground Model, Numerical Simulation**

I. Introduction

THERE have been attempts to improve the operational efficiency of construction projects and plan response countermeasures for estimated damage following disasters through the utilization of accumulated electronic data, which constructs a digital twin that can reproduce a physical space in cyberspace and feedback the cyberspace simulation results to physical space [1]. In Japan, the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) is making progress in developing a data platform for the utilization of the vast amount of data available describing government-managed land, cities, transportation infrastructure, and weather (collectively referred to as infrastructure data) under MLIT's administrative jurisdiction [2]. The Land Infrastructure, Transport and Tourism Data Platform contains a broad variety of infrastructure data and is expected to be used to facilitate the three-dimensional visualization of infrastructures such as bridges, river dikes, buried piping etc., data hub functions, and information distribution functions. Another potential use of this suite of resources is in the construction of a model that can facilitate numerical analysis operations, such as design and maintenance controls. The necessary information for creating such a numerical analysis model is often contained in partial form in multiple pieces of infrastructure data, rather than in a single piece. Therefore, it is necessary to integrate infrastructure data stored in multiple discrete file formats. This integrated data is referred to as mediated data, to which a common data structure is assigned. The mediated data is used to construct analytical models for various numerical analyses. Three functionalities are necessary for the integration of infrastructure data: parsing, conversion to mediated data, and construction of analytical models. The present study utilizes a program developed by RIKEN (Data Processing Platform, DPP [3]) to develop a program that incorporates these three functions. DPP is a platform offering a set of fundamental resources necessary for the development of such programs.

The numerical model construction technique can be applied to a variety of structures. However, this study resulted in the development of a program designed to handle numerical analysis for simulating the behavior of ground sites. There have been many attempts to develop a geological model from digital data. Chang et al. [4] developed a web-based geographic information system (GIS) application for efficient management of borehole and geological data. They archived more than 10,000 boreholes and geological data into the database for an urban area of Seoul. Merritt et al. [5] developed the geological framework models that integrated geochemical, physical property, and hydrogeological data obtained from the digitized borehole, map, and mining data in an area of Glasgow to help answer the geoenvironmental questions. The engineering geological classification of the superficial deposits is visualized in the 3D model. Jones et al. [6] visualized multi-scale geological models spanning orders of magnitude from outcrop to regional scale by combining a large number of different geological and geophysical data sources. The quantitative

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analysis of geological structures and the geospatial analysis of fracture arrays have been conducted in the case studies from northeast England and Northwest Scotland. El May et al. [7] produced uniform engineering geological maps from information such as the nature of superficial materials, topography, drainage network, water table level, seismotectonic conditions, geotechnical properties, and correlations derived from borehole stratigraphic information for rational urban planning and development. The areas at risk of landslides, flooding, the ground settlement were identified from the maps. Andersen et al. [8] constructed a detailed high-resolution 3D geological voxel model from geophysical data in conjunction with GIS data and used it for future development planning. In these studies, geological models were constructed based on borehole data and geological data, and the visualization of geological structures and classification have been mainly performed. The method proposed in this research not only classifies geological structures but also includes the estimation of basic geotechnical parameters so that numerical simulations can be performed smoothly using the constructed models. The software functions by constructing a three-dimensional grid model of a section of the ground based on the borehole data obtained through ground surveys. Simulations using three-dimensional numerical model of the ground can be useful in design, construction, and maintenance of embankments, cut-slopes, tunneling, and other works. To support the automation of underground construction and tunneling, it is important to integrate the ground model with the Building Information Modeling (BIM) for simulation. A tunneling project uses real-time simulations during construction to support decisions regarding the steering of a tunnel boring machine (TBM) [9]. Applying the BIM based design approach to the case of an underground line, a detailed tunnel structure model integrated with geological-geotechnical information for the definition of the subsoil was imported into a finite element model to perform deformation analysis [10]. The ground model used in the above simulations is made up of several layers based on borehole data and stratigraphic data, and geotechnical material parameters are provided to each layer in the simulation. The ground model proposed in this paper is a grid model, in which the coordinate values, soil classification, and material parameters are assigned to each regularly aligned grid point, which makes it easy to convert to a finite element model. It is also expected to be easy to convert the grid model to be applied to particle method such as the moving particle semi-implicit (MPS), the smoothed particle hydrodynamics (SPH) etc.

For example, tunneling by a TBM in an urban environment needs to limit the risk of construction-induced damage to residential and commercial areas. Therefore, an efficient computational model is needed to accurately predict the response of aboveground and existing infrastructure to tunneling, and techniques to automatically generate three-dimensional geotechnical model is essential.

The rest of this article is structured as follows: Section II introduces the DPP and the overall configuration of the developed program. Section III describes the process by which borehole data is parsed. Section IV describes the method for determining material parameters. Section V provides an explanation of the grid ground model mediation data structure. Section VI offers the conclusions drawn from the present study and describes its future prospects.

II. DPP and Overall Diagram of Developed Program

DPP is an interpreter language developed not only for general use of data, but also for use in large-scale numerical analysis programs that require the adoption of specialized data formats for optimization of analysis efficiency. As shown in Fig. 1, DPP can flexibly link heterogeneous data and heterogeneous programs by using a methodology of data abstraction based on automatic conversion of description formats, instead of standardizing data description in a uniform format. Not only can it implement the same functionality as existing extract transform load (ETL) tools, but it can also make the data more applicable to a wider range of applications. The DPP user can write simple scripts for executing various operations on the data. If the user's desired data processing operation is already built into the DPP, the user needs to only write a script for such an operation. Otherwise, the DPP program must be modified. Thus, DPP is a server-client type program.

The overall diagram of the program developed in this study is shown in Fig.2. The data processing consists of data parsing, conversion, integration, and model construction. In the case of geotechnical response analysis, the main data consists of borehole data, various test values, and commonly used default values in the extended markup language (XML), CSV formats. After the data is converted and integrated, it can be used as an input file for simulation and visualization.

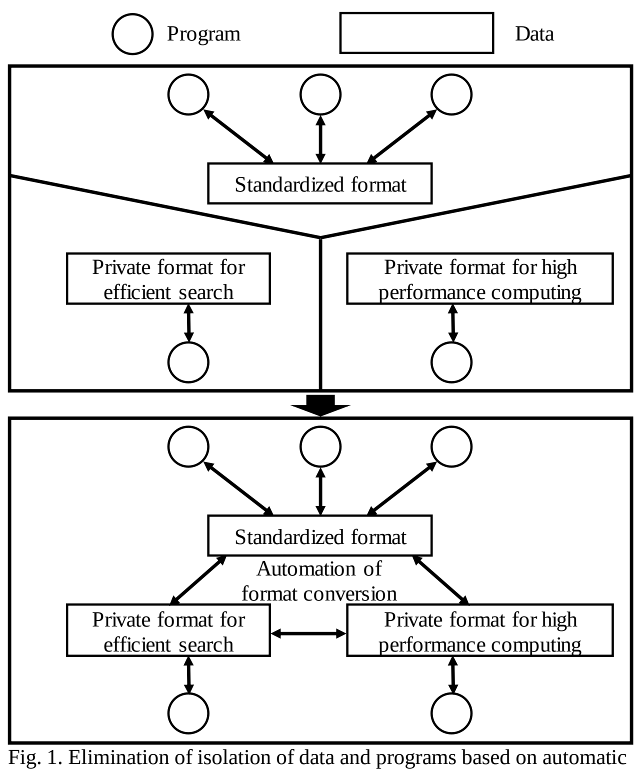


Fig. 1. Elimination of isolation of data and programs based on automatic conversion of description formats [3]

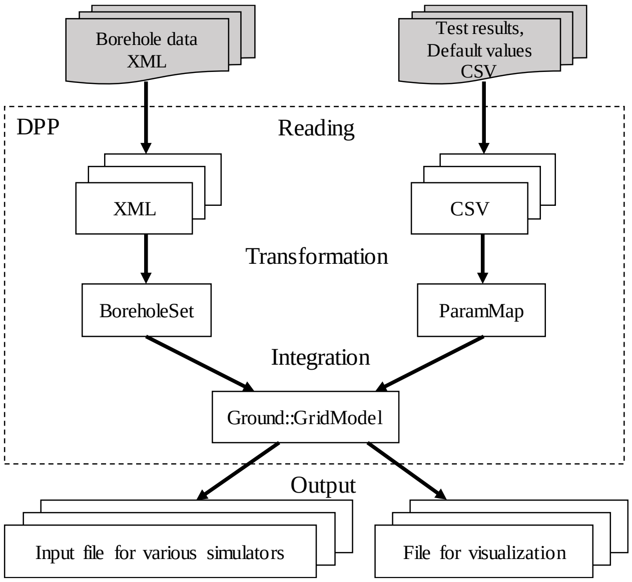


Fig. 2. Overall diagram of the developed program

III. Reading of Borehole Data

As shown in Fig. 3, when using the Land Infrastructure, Transport, and Tourism Data Platform, the points at which borehole data exist are indicated in the GIS. Selecting a point allows for the data to be downloaded in the XML format for describing the borehole survey results and the borehole map as a PDF file containing a graphic depiction of the data.

It is described below that the borehole data parsing function of DPP based on the borehole data corresponding to the location for coordinates 135°16’19.9” longitude and 34°43’0.736” latitude.

The script diagrammed in Fig. 3 can be used to read and output borehole data. The first three lines load the necessary shared libraries. Line 4 uses the BoreholeXML function to read an XML file with a specified file name as an argument and converts it to bdata, a DPP borehole data object. A DPP object is an instance of a data type defined in DPP that can be handled in the execution of a script. Functions defined in DPP that can be handled by scripts, such as the BoreholeXML function, are referred to as DPP functions. The BoreholeXML function reads the file and stores it in an XML DPP object and then converts the XML DPP object to a BoreholeSet DPP object. An XML DPP object is simply structured data comprised of tag names and corresponding value pairs, which can be converted into a BoreholeSet DPP object as borehole data. In this instance, a file name is passed as an argument to the BoreholeXML function. However, by specifying a directory name instead, all XML files in the specified directory can be read and converted into a single DPP object. On Line 5, bdata is output in the standard mode. When the borehole data is processed by the script shown in Fig. 4, latitude, longitude, maximum depth, borehole elevation, borehole water level, standard penetration test results, and soil type classification are output as described in Fig. 5.

Fig. 3. Land Infrastructure, Transport and Tourism Data Platform

```
1 library(“Quantity”);
2 library(“XSD”);
3 library(“Ground”);
4 bdata = BoreholeXML( “input.xml” );
5 Print( bdata );
```

Fig. 4 Script for reading borehole data

```
Latitude: 344300.736 DMS  Longitude: 1351649.914 DMS
Max. Depth:                        2.02000e+01 m
Elevation of borehole top:         3.44000e+00 m
Elevation of water table:          1.26000e+00 m
Standard Penetration Test:
Depth:      2.05500e+00 m  N-value:      8
Depth:      2.80000e+00 m  N-value:      11
Depth:      3.55000e+00 m  N-value:      28
                         ⋮
Depth:      2.00000e+01 m  N-value:      50
Classification of soil and rock
Upper depth: 0.00000e+00 m Lower depth: 1.80000e+00 m
Name: Backfill Symbol: FI Code: 09500
Upper depth: 1.80000e+00 m Lower depth: 2.90000e+00 m
Name: Silt mixed sand Symbol: S-M Code: 02104
Upper depth: 2.90000e+00 m Lower depth: 4.60000e+00 m
Name: Silt mixed gravelly soil Symbol: GF-M Code: 01004
                         ⋮
Upper depth: 1.61300e+01 m Lower depth: 2.02000e+01 m
Name: Gravelly soil Symbol: G Code: 01000
```

Fig. 5 Information of borehole data output by the script in Fig. 4

IV. Determination of Material Parameters

Use of a numerical analysis software for simulating terrain behavior requires the creation of an analytical model, and the grid ground model, which is automatically constructed in this study, serves as the basic mediated data for the creation of such an analytical model. These ground analysis software applications incorporate a constitutive model describing the characteristics of ground material. Many constitutive models have been proposed, including the original Cam-clay model [11].

Each of these structural models require discrete material parameters, and information relating to the parameters of typical ground materials (in this study: N-value N, Unit weight γ_t, Grain size D_{20}, Internal friction angle ϕ', Compression index λ, Poisson's ratio ν, Void ratio e, Coefficient of Earth pressure at rest K_0, Initial coefficient of Earth pressure K_i, Over consolidation ratio OCR, Initial vertical effective stress σ'_{vi}, Vertical effective stress in pre-consolidated state σ'_{v0}, Coefficient of permeability k) was loaded as mediated data. While these material parameters can be determined by conducting the necessary laboratory tests, the results for this purpose are included in the borehole results only in exceedingly rare instances. As such, the general ground material parameters are estimated in the manner shown in Fig. 6. This is a method for estimating the material parameters of primarily sandy soil by applying an equation based on the correlation with quantities such as N values, when the results of laboratory tests are insufficient to obtain the necessary material parameters [12]. A similar method for estimating the material parameters of soil containing clay was proposed by Iizuka et al. [13].

While the parameters of latitude, longitude, maximum depth, borehole elevation, borehole water level, standard penetration test results, and classification of soil can be read from borehole data, this information is not sufficient to estimate typical ground material parameters. Supplementary information gathered from other data sources would become necessary if the data used as a basis for constructing the analytical model, such as borehole data, lacks the necessary information. These include separately conducted density testing, consolidation testing, and permeability testing. Such information may not be contained in borehole data XML files but may be present in scientific reports or papers. Estimation of ground material parameters involves searching such reports and papers, reviewing tables and graphs, and applying numerical values. The result of this process is the determination of the material parameters to be applied, provided that certain conditions are met. In this study, the combination of these conditions and the material parameters to be applied (referred to as a "parameter map") is saved in a CSV file and used to create the analytical model.

Fig. 7 shows an example of a CSV with the conditions and material parameters to be applied. In Fig. 7(a), the rows with the same ID indicate an OR Boolean relationship, and each respective column indicates an AND relationship. The

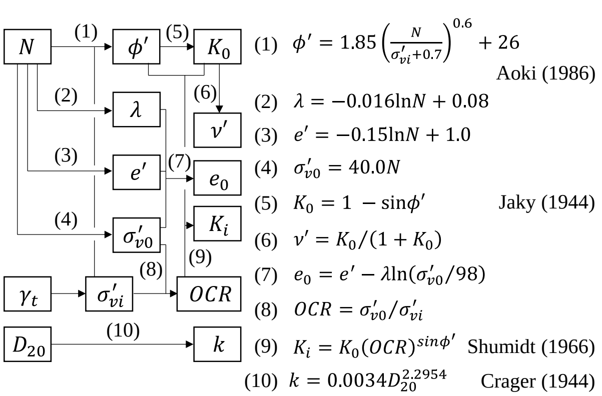


Fig. 6 Chart to determine material parameters from mainly N-value for sandy soil

ID	Soil Type Name	NValue
1	Sandy soil	[30 : 50)
2	Sandy soil	[10 : 30)
2	Sand	[10 : 30)
3	Clay	[30:]
4	Gravel	

(a) condition.csv

ID	Gamma_t	D20	Category
1	19.0 kN/m3	0.4 mm	S
2	18.0 kN/m3	0.4 mm	S
3	19.0 kN/m3	0.005 mm	C
4	18.0 kN/m3	2.0 mm	G

(b) parameter.csv

Fig. 7 Parameter Map (a) CSV file for conditions (b) CSV file for material parameters to apply when the condition is satisfied

```
1 library("Quantity");
2 library("CSV");
3 library("ParamMap");
4 table = ParamMap( "condition.csv", "parameter.csv" );
5 Print( table );
```

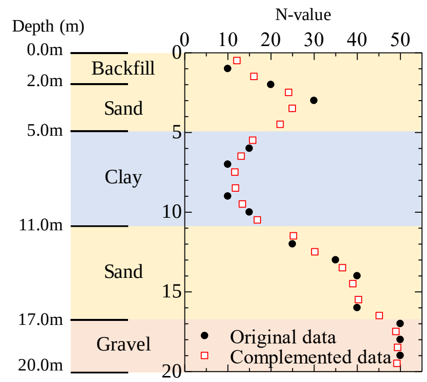
Fig. 8 Script for reading Parameter Map

condition corresponding to ID=1 is as follows:
$Soil\ Type\ Name = Sandy\ Soil \cap (N \geq 30\ \cap N < 50)$,
while the condition corresponding to ID=2 is:
$\{Soil\ Type\ Name = Sandy\ Soil \cap (N \geq 30 \cap N < 50)\}$
$\cup \{Soil\ Type\ Name = Sand \cap (N \geq 30 \cap N < 50)\}$.
The parameters corresponding to the respective IDs in Fig. 7(b) are applied when these conditions are met.

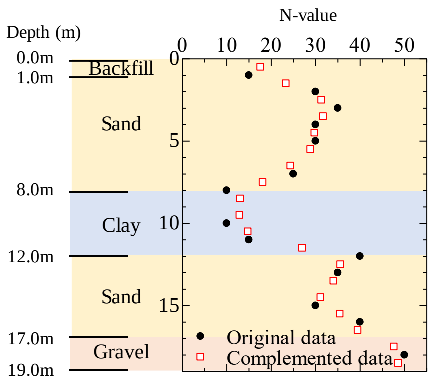
Fig. 8 shows the script used by DPP to read this CSV file and generate an output based on its contents. As in the script displayed in Fig. 5, the first three lines load the necessary shared libraries. Line 4 uses the ParamMap function to read the two CSV files and convert them into a table of ParamMap DPP objects. Line 5 outputs this table in the standard mode.

V. Grid Ground Model Construction

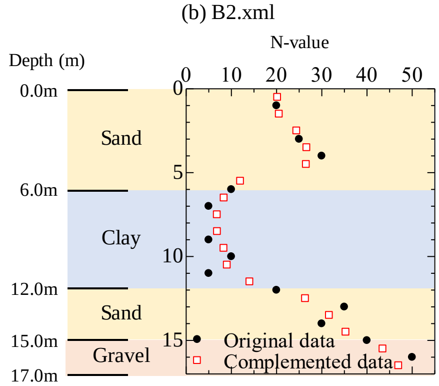
The grid ground model is constructed as the mediated data for the numerical analysis model. The grid ground model is comprised of data relating to typical ground material parameters in points arranged in a grid. It is described below that the process of constructing a grid ground model based on three units of hypothetical borehole data. Fig. 9 displays the hypothetical borehole data prepared for this purpose. As the N-values obtained because of standard penetration testing of this borehole data are not necessarily obtained at the depth where the grid points are situated, the N-values are complemented at their depth location. The inverse distance weighted method was used for this complementation. Soil and rock type classification was also defined for each grid point. The result of this complementation based on the borehole data also described in Fig. 9. The grid points are oriented in 1.0m intervals, with the



(a) B1.xml



(b) B2.xml



(c) B3.xml

Fig. 9 Borehole data (a) Longitude: 135°16′50.0″, Latitude: 34°43′0.0″, Elevation of borehole top: 3.0m (b) Longitude: 135°16′51.0″, Latitude: 34°42′59.5″, Elevation of borehole top: 2.0m (c) Longitude: 135°16′50.4″, Latitude: 34°42′59.0″, Elevation of borehole top: 0.0m, and distribution of N-value complemented by the inverse distance weighted method

uppermost point at 2.5m above sea level.

The "category" for each point is determined as a result of the application of the parameter map shown in Fig. 10(a), (b) to the borehole data with the soil/rock type classification N-value information for the grid point elevations. Next, the N-values were complemented via the inverse distance weighted method in the horizontal plane at each grid point elevation, after which the N-values for all grid points were obtained.

The category for each grid point was also defined as the category of the point with the nearest borehole data. Moreover, the corresponding material parameters were applied to each conforming grid point through use of the parameter map shown in Fig. 10(c), (d). Other material parameters were calculated based on these material parameters, according to the material parameter determination chart displayed in Fig. 5. A grid ground model was constructed through this process from three units of hypothetical borehole data prepared.

Fig. 11 displays the DPP script for creating a grid ground model. The first five lines serve to load the necessary shared libraries. Line 6 executes the reading and conversion to DPP object bdata of three XML files containing borehole data.

The argument for the DPP function BoreholeXML is the name of the directory in which the three XML files are stored. The seventh line results in the reading of the CSV file shown in Fig. 10(a), (b) and converts its contents to the DPP object- table1. The eighth line is similar and results in the reading of the CSV file shown in Fig. 10(c), (d) and its conversion to the DPP object- table2. Line 9 causes bdat and table1 to be integrated to create a grid ground model, which is then used as the DPP object- gmodel. Line 10 results in the unit weight γ_t and grain size D_{20} at each grid point to be determined via application of table2 to gmodel, as well as the calculation of other material parameters. Line 11 results in the information (coordinates and material parameters) corresponding to all grid points comprising the grid ground model to be output to a CSV file. Lastly, Line 12 results in the information for all grid points to be output to a file in point cloud data format. As "Nvalue" is

ID	Soil Type Name
1	Sand
2	Clay
3	Gravel
4	Backfill

(a) condition1.csv

ID	Category
1	S
2	C
3	G
4	S

(b) parameter1.csv

ID	Category	NValue
1	S	[30:]
2	S	[:30)
3	C	
4	G	

(c) condition2.csv

ID	Gamma_t	D20
1	19.0 kN/m3	0.4 mm
2	18.0 kN/m3	0.4 mm
3	17.0 kN/m3	0.005 mm
4	18.0 kN/m3	2.0 mm

(d) parameter2.csv

Fig. 10 Parameter Map

```
1  library("Quantity");
2  library("XSD");
3  library("CSV");
4  library("ParamMap");
5  library("Ground");
6  bdata = BoreholeXML( dir_xml );
7  table1 = ParamMap( "condition1.csv", "parameter1.csv" );
8  table2 = ParamMap( "condition2.csv", "parameter2.csv" );
9  gmodel = Ground::GridModel( bdat, table1, 5 );
10 gmodel.Apply( table2 );
11 OutputCSV( gmodel, "grid.csv" );
12 OutputParticle( gmodel, "grid.particles", param_name="Nvalue");
```

Fig. 11 Script for constructing the grid ground model

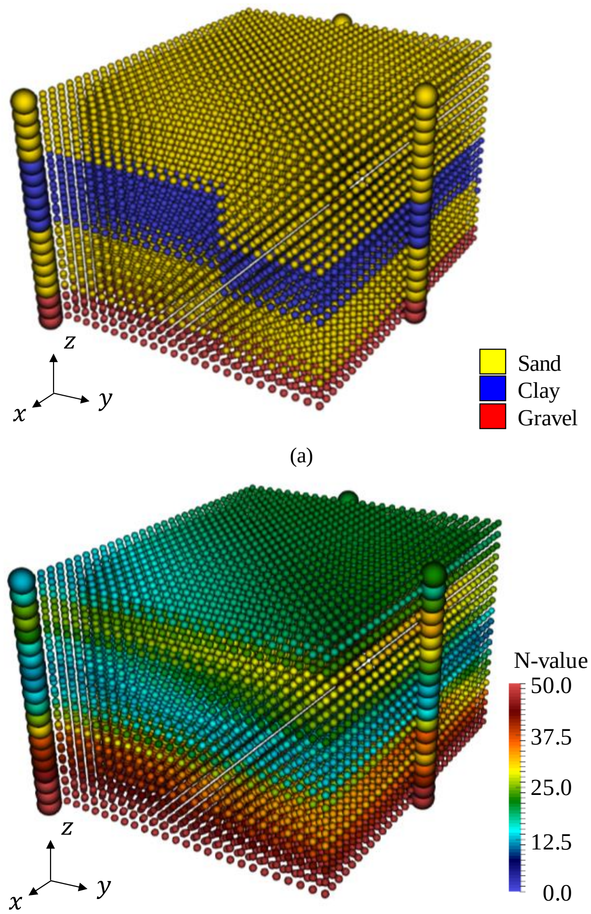


Fig. 12 Ground grid model (a) Category (b) Distribution of N-value

specified as an argument, this results in the output of the N-value for each point. Information relating to the various material parameters calculated can also be output by manipulating this argument.

The distributions for the "category" and N-value output produced by this script are displayed in Fig. 12. Grid points are placed at 1m intervals in the x, y planes. Each interval can also be applied to the Ground::GridModel function as an argument.

VI. Conclusion

This study developed a program capable of utilizing a data processing platform to read, transform, and integrate data to create mediated data that conforms to a common data structure. Using the developed program, a three-dimensional ground grid model was constructed from the results of ground surveys with borehole data serving as mediated data. This model incorporates grid points containing information describing typical ground material parameters used as a basis for the creation of analytical models for numerical analysis software programs to simulate terrain behaviors.

Because the ground model presented in this study is a grid, it can be easily converted to a finite element model, and can be automatically generated from the ground investigation results, so that the numerical model can be updated almost without any cost when the ground investigation results such as borehole data are added or updated. Therefore, it is also applicable for artificially changed ground conditions and can cover the uncertainty of the material parameters of the ground. Because the grid ground model is created as mediator data, it can be converted into a numerical model for direct use in other simulators by describing the conversion between the model for each simulator and the grid ground model using the DPP.

Although the ground surface of the grid ground model constructed is horizontal, we plan to incorporate digital elevation map (DEM) data in the future to allow for the reflection of the shape of the ground surface in the model. In addition, we plan to expand the library to simulators beyond ground response analysis, such as bridge response analysis and riverbed fluctuation analysis, by expanding the types of files that can be read by the DPP.

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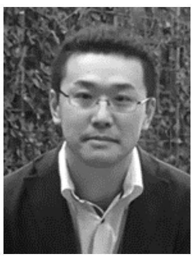

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