Large-scale Stabilized Multi-Physics Earthquake Simulation for Digital Twin

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Abstract. The development of computing environments and computational techniques, together with data observation technology, big data and extreme-scale computing (BDEC) has gained immense attention. An example of BDEC is the digital twin concept of a city, a high-fidelity model of the city developed based on a computing system for the BDEC. The virtual experiments using numerical simulations are performed there, whose results are used in decision making. The earthquake simulation, which entails the highest computational cost among numerical simulations in the digital twin, was targeted in this study. In the multi-physics earthquake simulation considering soil liquefaction, the computation could become unstable when a high resolution is used for spatial discretization. In the digital twin, high-resolution large-scale simulation is performed repeatedly, and thus, it is important to avoid such instability due to the discretization setting. In this study, an earthquake simulation method was developed to stably perform high-resolution large-scale simulations by averaging the constitutive law spatially based on a non-local approach. The developed method enables us to stably perform simulations with high-resolution of the order of 0.1 m and obtain a converged solution.

Keywords: Digital twin · Finite element method · Non-local approach.

1 Introduction

With the development of computing environments and computational techniques, large-scale physics-based simulations have become possible. In addition, as the huge quantity of data has been and will be collected, the big data and extreme-scale computing (BDEC) [2] has gained attention in a wide range of research fields. In the BDEC, it is expected that a huge amount of observed data and machine learning results from these observed data are integrated into physics-based simulations, which enables us to perform more reliable simulations. One example of the BDEC is the digital twin concept of a city, where high-fidelity

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model of the city is developed on a computing system for the BDEC. The internal state of the digital twin, such as river level and groundwater level, is updated based on the data observed in real time. Virtual experiments on the digital twin are performed using numerical simulations, whose results are used for decision making.

In this study, the earthquake simulation, which requires the highest computational cost among virtual experiments of the digital twin, was targeted. To overcome huge computational cost of the earthquake simulation, various methods have been developed using different discretization scheme such as the finite element method (FEM) [9, 7] and finite different method [5, 4, 12, 13]. We have developed fast soil liquefaction simulation methods for CPUs [15] and GPUs [16] based on FEM-based scalable earthquake simulation methods [12, 13]. In this study, based on the GPU-based soil liquefaction simulation method [16], we developed a method for computing the risk from earthquakes considering soil liquefaction, which fluctuates as the groundwater level changes over a year. It is assumed that the groundwater level is one of the internal state variables of the digital twin and is updated based on groundwater level measured at several observation points. As frequency of localized torrential rain is increasing due to the climate change, it is concerned that the water level exceeds the assumption during the seismic design for a certain period of time. In other words, the risk from earthquakes is not static, but it changes dynamically. The earthquake simulations considering complex multi-physics, such as the one presented in this study, are expected to play an important role in assessing such dynamic risk. In previous studies, the groundwater level was often set arbitrarily such as "2 m below the ground surface". In this study, the groundwater level is computed using the seepage analysis to perform more accurate earthquake simulations.

Various kinds of constitutive laws have been developed to model a complex nonlinear behavior of materials in numerical simulations. However, some of them could cause instability and divergence of the computation in high-resolution simulations. The constitutive law [11, 10] used in this study is for multi-physics soil liquefaction analysis considering highly nonlinear soil behavior and the influence of excess pore water pressure, and can cause simulation instability. In the digital twin, it is required to stably perform large-scale simulations many times with high resolution using different sets of parameters, and therefore it is crucial to avoid such instability of simulation caused by the discretization setting.

We developed a stabilization method to overcome this problem. In the developed method, the constitutive law is spatially averaged based on a non-local approach, which has been developed in the field of continuum damage mechanics [14, 8]. By this averaging, the constitutive law is computed in a certain volume, not in a point, and thus, the developed method is expected to avoid the instability of simulation. Besides, the generalized alpha method [6], which can prescribe numerical dissipation for high-frequency modes, is adopted for time integration to further stabilize the analysis.

We performed earthquake simulation considering soil liquefaction using soil models with a different spatial resolution to demonstrate the capability of the de-

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veloped method. The simulations with the conventional method got unstable for high-resolution simulations and the results did not converge. On the other hand, the simulations using the developed method were stable even for the highest resolution of 0.125 m and the results converged as the resolution increased. For example, we performed a large-scale earthquake simulation using a soil-structure model that mimics an actual site near an estuary with 702 million degrees of freedom (DOFs). Here, 480 Nvidia Tesla V100 GPUs on AI Bridging Cloud Infrastructure [1] were used for computation.

2 Methodology

In the digital twin, the internal state is updated using observed data. In order to accurately assess the risk from an earthquake, the earthquake simulation needs to be performed repeatedly to reassess the risk as the internal state of the digital twin is updated; thus, fast and stable methods for earthquake simulation are required. In this study, the multi-physics earthquake simulation considering soil liquefaction was targeted as one of the problem settings in which the simulation instability could occur. We have developed fast soil liquefaction simulation methods [15, 16] based on large-scale simulation methods [12, 13]. In this study, we developed a stabilization method for multi-physics earthquake simulation of the digital twin based on the GPU-based fast earthquake simulation method [16] using a non-local approach [14, 8], which has been developed in the field of continuum damage mechanics.

2.1 Problem settings of the earthquake simulation

The earthquake simulation in this study uses the finite element method (FEM) with second-order unstructured tetrahedral elements. The FEM allows the use of models with complex 3D geometry and easy handling of nonlinear materials and a traction-free boundary condition. The generalized alpha method [6] adopted as the time integration method prescribes numerical dissipation for high-frequency modes and suppresses the instability caused by the high-frequency modes due to numerical errors. The target equation, which is the motion equation discretized by the FEM and the generalized alpha method, becomes

$$\boldsymbol{A}\delta\boldsymbol{u} = \boldsymbol{b}, \tag{1}$$

where,

$$\boldsymbol{A} = \frac{1-\alpha_{\mathrm{m}}}{\beta\ dt^2}\boldsymbol{M} + \frac{(1-\alpha_{\mathrm{f}})\gamma}{\beta\ dt}\boldsymbol{C}^{(n)} + (1-\alpha_{\mathrm{f}})\boldsymbol{K}^{(n)}, \tag{2}$$

$$\begin{aligned}\boldsymbol{b} &= (1-\alpha_{\mathrm{f}})\boldsymbol{f}^{(n+1)} + \alpha_{\mathrm{f}}\boldsymbol{f}^{(n)} - \boldsymbol{q}^{(n)} \\ &\quad + \boldsymbol{M}\left[\left(\frac{1-\alpha_{\mathrm{m}}}{2\beta} - 1\right)\boldsymbol{a}^{(n)} + \frac{1-\alpha_{\mathrm{m}}}{\beta\ dt}\boldsymbol{v}^{(n)}\right] \\ &\quad + \boldsymbol{C}\left[(1-\alpha_{\mathrm{f}})\left(\frac{\gamma}{2\beta} - 1\right)dt\boldsymbol{a}^{(n)} + \left(\frac{(1-\alpha_{\mathrm{f}})\gamma}{\beta} - 1\right)\boldsymbol{v}^{(n)}\right].\end{aligned} \tag{3}$$

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Here, $\boldsymbol{M}, \boldsymbol{C}$, and $\boldsymbol{K}$ are the matrices of mass, Rayleigh damping, and stiffness, respectively. $\delta\boldsymbol{u}$, $\boldsymbol{f}$, $\boldsymbol{q}$, $\boldsymbol{v}$, and $\boldsymbol{a}$ are the vectors of the displacement increment, external force, inner force, velocity, and acceleration, respectively, and dt is the time increment. $*^{(n)}$ is the variable $*$ in the n-th time step. $\alpha_{\mathrm{m}}, \alpha_{\mathrm{f}}, \beta$, and γ are parameters for the generalized alpha method, where $\alpha_{\mathrm{m}} = (2\rho_\infty - 1)/(\rho_\infty + 1)$, $\alpha_{\mathrm{f}} = \rho_\infty/(\rho_\infty + 1)$, $\beta = (1 - \alpha_{\mathrm{m}} + \alpha_{\mathrm{f}})^2/4$, $\gamma = 1/2 - \alpha_{\mathrm{m}} + \alpha_{\mathrm{f}}$. ρ_∞ is the spectral radius in the high-frequency limit, which was set 0.8 in this study. (For $\alpha_{\mathrm{m}} = \alpha_{\mathrm{f}} = 0$, the equation (1) matches the target equation that uses the Newmark beta method for the time integration.)

The target equation (1) is solved every time step to obtain $\delta\boldsymbol{u}$, and the variables are updated as follows:

$$\boldsymbol{u}^{(n+1)} = \boldsymbol{u}^{(n)} + \delta\boldsymbol{u}, \tag{4}$$

$$\boldsymbol{v}^{(n+1)} = \left(1 - \frac{\gamma}{2\beta}\right) dt\boldsymbol{a}^{(n)} + \left(1 - \frac{\gamma}{\beta}\right)\boldsymbol{v}^{(n)} + \frac{\gamma}{\beta\ dt}\delta\boldsymbol{u}, \tag{5}$$

$$\boldsymbol{a}^{(n+1)} = \left(1 - \frac{1}{2\beta}\right)\boldsymbol{a}^{(n)} - \frac{1}{\beta\ dt}\boldsymbol{v}^{(n)} + \frac{1}{\beta\ dt^2}\delta\boldsymbol{u}, \tag{6}$$

$$\boldsymbol{K}^{(n+1)} = \sum_e \int_{V_e} \boldsymbol{B}^{\mathrm{T}}\boldsymbol{D}^{(n+1)}\boldsymbol{B}\ \mathrm{d}V, \tag{7}$$

$$\boldsymbol{q}^{(n+1)} = \sum_e \int_{V_e} \boldsymbol{B}^{\mathrm{T}}\boldsymbol{\sigma}^{(n+1)}\ \mathrm{d}V. \tag{8}$$

Here $\boldsymbol{B}$ is the matrix used to convert the displacement into the strain. $\boldsymbol{D}$ is the elasto-plastic matrix and $\boldsymbol{\sigma}$ is the total stress, calculated from displacement using the constitutive law. The elasto-plastic matrix and total stress for soil above the groundwater level are calculated using the stiffness parameters that depend on the confining stress. Those for soil below the groundwater level are calculated using the stiffness parameter that are calculated with the excess pore water pressure model [11], in which the accumulated elastic shear work is the index of the progress of liquefaction. $\int_{V_e} * \,\mathrm{d}V$ represents volume integration in the e-th element.

2.2 Seepage analysis to compute the groundwater distribution

In the digital twin, the internal state of the model is updated based on the data observed in real time. In this study, the groundwater level, which fluctuates over a year, is targeted as an internal state variable. In conventional earthquake simulations, the groundwater level was often set arbitrarily such as "2 m below the ground surface". In this study, the groundwater level was computed through the seepage analysis to perform a more reliable simulation.

In the seepage analysis, water is assumed to be incompressible, and a steady flow is computed. By neglecting the vertical flow and integrating the equation of conservation of mass with respect to vertical direction, the target equation becomes

$$\boldsymbol{\nabla}\cdot(\boldsymbol{T}(h)\boldsymbol{\nabla}h) - Q(h) = 0, \tag{9}$$

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where,

$$\boldsymbol{T}(h) = \int_0^h \boldsymbol{K}\, dz, \tag{10}$$

$$Q(h) = \int_0^h q dz. \tag{11}$$

Here, h is the total hydraulic head, $\boldsymbol{K}$ is the tensor of permeability coefficient, and q is the outflow of water to the outside of the system. The two-dimensional distribution of the total hydraulic head is computed by discretizing equation (9) using the FEM with a structured grid, and is used as the groundwater level distribution. The groundwater level distribution is set constant over time during an earthquake simulation, assuming that an earthquake occurs in a relatively short time period compared to the groundwater level fluctuation.

2.3 Stabilization method for the earthquake simulation by averaging the constitutive law

In the earthquake simulations where the soil behaves highly nonlinear, the computation could get unstable and diverge, especially when the high resolution is used for spatial discretization. One cause of instability of such a simulation is the assumption that the constitutive law holds at all points in the domain, even though the soil is an inhomogeneous material and the constitutive law for soil describes the "average" relationship between the strain and stress in a certain volume (This means there is a range of resolution in which the constitutive law holds validly). In simulations with a relatively low resolution of the order of 1 to 10 m, the above assumption does not cause serious problems because each point represents a certain volume. However, in simulations with a high resolution of the order of 0.1 m, this assumption could lead to instability of simulation as the resolution for simulation is outside the valid range of resolutions, for which the constitutive law holds. Even though the simulation does not always get unstable when the resolution is outside the valid range, large-scale simulations are more likely to get unstable compared to small-scale simulations. In the digital twin, it is required to stably perform large-scale simulations many times with high resolution; thus it is important to avoid such instability of simulation caused by the discretization setting.

In this study, the multi-physics earthquake simulation considering soil liquefaction was targeted as one of the problem settings in which the simulation instability can occur. The constitutive law [11, 10] that considers the high nonlinearity of soil behavior and the influence of excess pore water pressure was used. The constitutive law consists of the excess pore water pressure model and multi-spring model, and describes soil liquefaction under undrained conditions. Based on the excess pore water pressure model, the soil stiffness parameters $\boldsymbol{\theta}$ (bulk modulus, shear modulus, and shear strength) are calculated from the accumulated value of plastic shear work, which is used as the index of the progress of

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soil liquefaction. With the multi-spring model $\boldsymbol{f}$, the stress $\boldsymbol{\sigma}$ and elasto-plastic matrix $\boldsymbol{D}$ are calculated using the stiffness parameters $\boldsymbol{\theta}$ and strain $\boldsymbol{\varepsilon}$ as follows:

$$\boldsymbol{\sigma} = \boldsymbol{f}(\boldsymbol{\varepsilon}; \boldsymbol{\theta}) \tag{12}$$

$$\boldsymbol{D} = \frac{\partial \boldsymbol{f}(\boldsymbol{\varepsilon}; \boldsymbol{\theta})}{\partial \boldsymbol{\varepsilon}} \tag{13}$$

When the conventional method is used for simulation with high resolution of the order of 0.1 m, the instability could occur due to extremely large strain in several elements caused by the following cycle: (1) the soil liquefies; (2) the soil stiffness is reduced; (3) the strain gets large; (4) the plastic shear work (which is used as the index of the progress of liquefaction) is accumulated; (5) the soil liquefies further. This problem happens due to the assumption that the constitutive law holds at all points in the domain, which is not suitable in high-resolution simulations.

In the developed method, the constitutive law is averaged using a non-local approach [14, 8], which has been developed in the field of continuum damage mechanics, according to the following steps:

1. The stiffness parameters $\boldsymbol{\theta}(\boldsymbol{x})$ at each position $\boldsymbol{x}$ are calculated based on the excess pore water pressure model in the same way as the conventional constitutive law.
2. The stiffness parameters $\boldsymbol{\theta}$ are averaged and the non-local stiffness parameters $\bar{\boldsymbol{\theta}}$ are calculated from equation (14).

$$\bar{\boldsymbol{\theta}}(\boldsymbol{x}) = \int_V \alpha(\boldsymbol{\xi}; \boldsymbol{x}) \boldsymbol{\theta}(\boldsymbol{\xi}) \ \mathrm{d}\boldsymbol{\xi}, \tag{14}$$

Here $\alpha(\boldsymbol{\xi}; \boldsymbol{x})$ is a non-negative function that has the maximum value at $\boldsymbol{\xi} = \boldsymbol{x}$, monotonically decreases with respect to $||\boldsymbol{\xi} - \boldsymbol{x}||$ and satisfies $\int_V \alpha(\boldsymbol{\xi}; \boldsymbol{x}) \ \mathrm{d}\boldsymbol{\xi} = 1$. The function below was used in this study.

$$\alpha(\boldsymbol{\xi}; \boldsymbol{x}) = \frac{\alpha_0(||\boldsymbol{\xi} - \boldsymbol{x}||)}{\int_V \alpha_0(||\boldsymbol{\zeta} - \boldsymbol{x}||) \ \mathrm{d}\boldsymbol{\zeta}} \tag{15}$$

$$\alpha_0(r) = \begin{cases} \left(1 - \dfrac{r^2}{R^2}\right)^2 & \text{if } 0 \leq r \leq R \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

Here R is the parameter that determines the range of averaging. $R = 1$ m was used in this study.
3. The stress $\boldsymbol{\sigma}$ and elasto-plastic matrix $\boldsymbol{D}$ are calculated using the non-local stiffness parameters $\bar{\boldsymbol{\theta}}$ instead of the stiffness parameters $\boldsymbol{\theta}$.

$$\boldsymbol{\sigma} = \boldsymbol{f}(\boldsymbol{\varepsilon}; \bar{\boldsymbol{\theta}}) \tag{17}$$

$$\boldsymbol{D} = \frac{\partial \boldsymbol{f}(\boldsymbol{\varepsilon}; \bar{\boldsymbol{\theta}})}{\partial \boldsymbol{\varepsilon}} \tag{18}$$

By this averaging, the constitutive law is calculated in a certain volume even in high-resolution simulations, which is expected to avoid the instability of simulation. Specifically, even if the soil liquefies locally, the soil stiffness reduction is

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suppressed by the averaging. Thus, in the cycle that causes extreme strain (i.e., (1) the soil liquefies; (2) the soil stiffness is reduced; (3) the strain gets large; (4) the plastic shear work is accumulated; (5) the soil liquefies further), the step from (1) to (2) is less likely to happen and the extreme strain is expected to be prevented. The computational complexity of this algorithm is $O((R/\Delta x)^3)$ and the amount of MPI communication is $O(R/\Delta x^3)$, where Δx is spatial resolution of the soil-structure model.

3 Numerical Experiment

Numerical experiments were carried out to demonstrate the capability of the developed method. It is shown that the developed stabilization method was able to stably perform the simulation; however the conventional method failed to perform when the spatial resolution was high. A large-scale high-resolution earthquake simulation with a soil-structure model mimicking an actual site near an estuary was performed. Here, the distribution of groundwater level computed by the seepage analysis was used. The seismic wave observed during the 1995 Hyogo-ken Nambu earthquake [3] was used as an input wave for all simulations.

3.1 Comparison of the conventional method and developed method

Earthquake simulations considering soil liquefaction were performed using the ground model shown in Fig. 1. Table 1 shows the material properties. The groundwater level was set 2 m below the ground surface. The time increment was 0.001 s. Simulations with the conventional method and developed method were performed with four different spatial resolutions of 1 m, 0.5 m, 0.25 m, and 0.125 m. The difference between the conventional and developed methods is (a) the computation of stress $\boldsymbol{\sigma}$ and elasto-plastic matrix $\boldsymbol{D}$ with the constitutive law and (b) the time integration method. In the conventional method, the stress

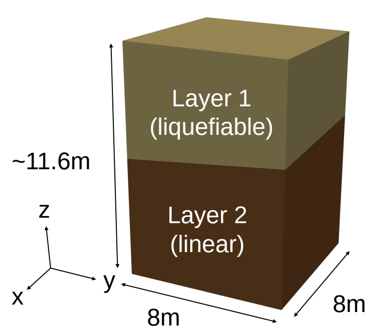

Fig. 1: The model used in the comparison of the developed method and conventional method.

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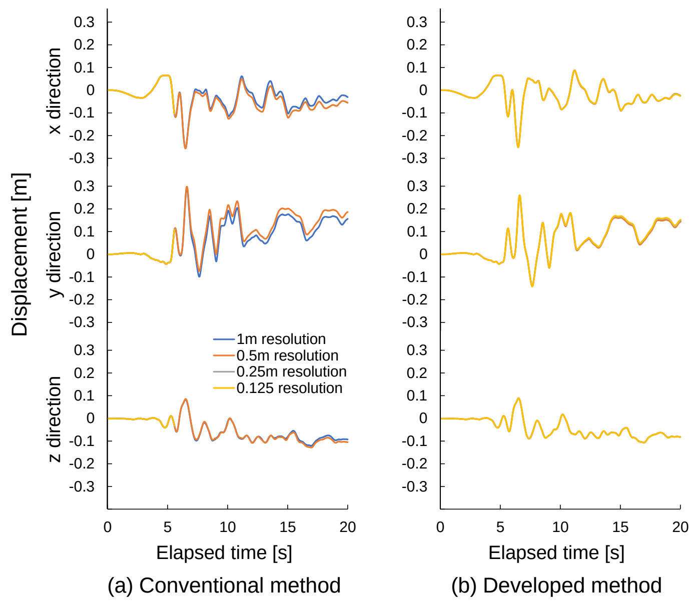

Fig. 2: Comparison of the time history of displacement at the center of the ground surface.

$\boldsymbol{\sigma}$ and elasto-plastic matrix $\boldsymbol{D}$ are computed using the stiffness parameters $\boldsymbol{\theta}$, which are not averaged, using equations (12, 13), and the Newmark beta method was used for time integration. In the developed method, the stress $\boldsymbol{\sigma}$ and elasto-

Table 1: Model properties

(a) Soil profile properties. ρ: density, $V_\mathrm{p}, V_\mathrm{s}$: velocity of primary and secondary waves.

	ρ[kg/m^3]	V_p[m/s]	V_s[m/s]	constitutive law
Layer1	1500	—	—	nonlinear (liquefiable)
Layer2	1800	1380	255	linear
Bedrock	1900	1770	490	linear

(b) Parameters for the nonlinear constitutive law. $G_\mathrm{ma}, K_\mathrm{ma}$: elastic shear modulus and bulk modulus at a confining pressure of σ'_ma, σ'_ma: reference confining pressure, m_K, m_G: parameters for nonlinearity, ϕ_f: shear resistance angle.

G_ma[GPa]	K_ma[GPa]	σ'_ma[kPa]	m_G	m_K	ϕ_f
106.6	278.0	-37	0.5	0.5	40°

(c) Parameters for liquefiable propety. ϕ_p: phase transformation angle, S_min, p_1, p_2, c_1 and w_1: parameters for dilatancy, ρ_f: density of pore water, n: porosity, K_f: bulk modulus of pore water.

ϕ_p	S_min	p_1	p_2	c_1	w_1	ρ_f[kg/m^3]	n	K_f[GPa]
28°	0.01	0.5	0.65	3.97	7.0	1000	0.45	2200

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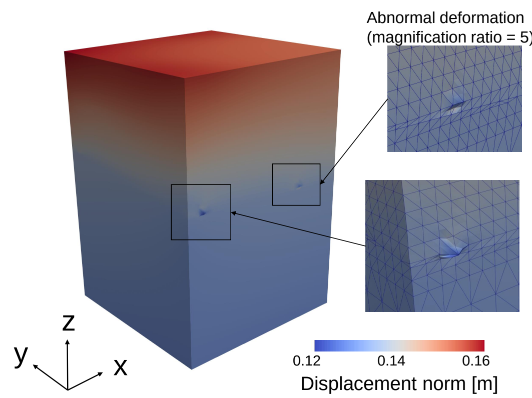

Fig. 3: Displacement norm and deformation when the computation was abnormally terminated in the simulation with 0.125-m resolution using the conventional method.

plastic matrix $\boldsymbol{D}$ are computed using the non-local stiffness parameters $\bar{\boldsymbol{\theta}}$ using equations (17, 18), and the generalized alpha method is used for time integration.

Fig. 2 shows the time history of the displacement at the center of the ground surface. In the conventional method, the iteration of the conjugate gradient method was not converged in solving the target equation and the computation was abnormally terminated around $t = 5.6$ s in simulations with a resolution of 0.25 m and 0.125 m. Also, the simulation results did not converge as the resolution increased (Fig. 2(a)). Fig. 3 depicts the displacement when the computation was abnormally terminated in the 0.125-m-resolution simulation. Several elements deformed to an extreme extent due to the instability. On the other hand, with the developed method, the abnormal termination did not occur and the simulation results converged, as shown in Fig. 2(b). Hence, the developed method enables to stably perform high-resolution simulation and obtain converged results.

3.2 Application: multi-physics earthquake simulation with a large-scale high-resolution soil-structure model

Earthquake simulation using a large-scale high-resolution soil-structure model which mimicked an actual site near an estuary was performed. The spatial resolution was 0.5 m, with which the simulation using the conventional method could be unstable. The soil structure model shown in Fig. 4 was used; the model has 702,192,969 DOFs and 172,929,616 elements. Table 2 shows the material properties and the same parameters for liquefiable property as the previous section (shown in Table 1(c)) were used. The seepage analysis of the groundwater was conducted assuming that layer 1 was an unconfined aquifer to obtain the groundwater level distribution, as shown in Fig. 5. Using the developed method, the

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Table 2: Model properties of the application

(a) Soil profile properties. ρ: density, $V_{\mathrm{p}}, V_{\mathrm{s}}$: velocity of primary and secondary waves.

	ρ[kg/m^3]	V_{p}[m/s]	V_{s}[m/s]	constitutive law
Layer 1	1500	—	—	nonlinear(liquefiable)
Layer 2	1500	—	—	nonlinear(non-liquefiable)
Bedrock	1900	1770	490	linear
water	1000	1500	100	linear
wharf	2100	3378	2130	linear

(b) Parameters for the nonlinear constitutive law. $G_{\mathrm{ma}}, K_{\mathrm{ma}}$: elastic shear modulus and bulk modulus at a confining pressure of σ'_{ma}, σ'_{ma}: reference confining pressure, m_K, m_G: parameters for nonlinearity, ϕ_{f}: shear resistance angle.

	G_{ma}[GPa]	K_{ma}[GPa]	σ'_{ma}[kPa]	m_G	m_K	ϕ_{f}
layer 1	106.6	278.0	-37	0.5	0.5	35°
layer 2	117.0	327.2	-419	0.5	0.5	40°

seismic response considering soil liquefaction for 20 s (20,000 time steps) was simulated with the time increment of 0.001 s. Fig. 6 shows the displacement on the ground surface at t =20 s.

The computation was parallelized with 480 MPI processes × 1 GPU per 1 MPI process = 480 GPUs, and was conducted on 120 computing nodes of a GPU-based supercomputer AI Bridging Cloud Infrastructure (ABCI)[1]. (Each computing node of ABCI consists of four NVIDIA Tesla V100 GPUs and two Intel Xeon Gold 6148 CPUs.) The computation time was 4 h 20 min. The computation time for the non-local approach was 18 min (6 min for the initial setting and 0.023 s/time step×30,000 time steps = 12 min), which is 7% of the computation time for the whole analysis. It is indicated that the developed method enables us to stably perform large-scale high-resolution earthquake simulation

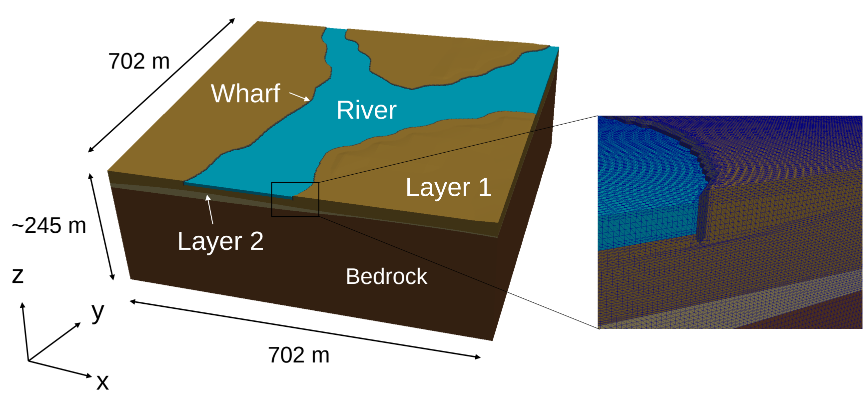

Fig. 4: The model used in the application.

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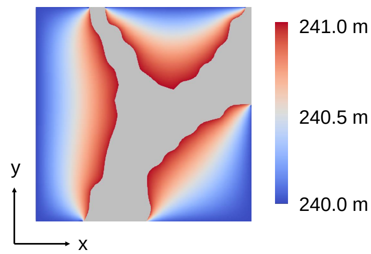

Fig. 5: Groundwater level distribution computed by the seepage analysis.

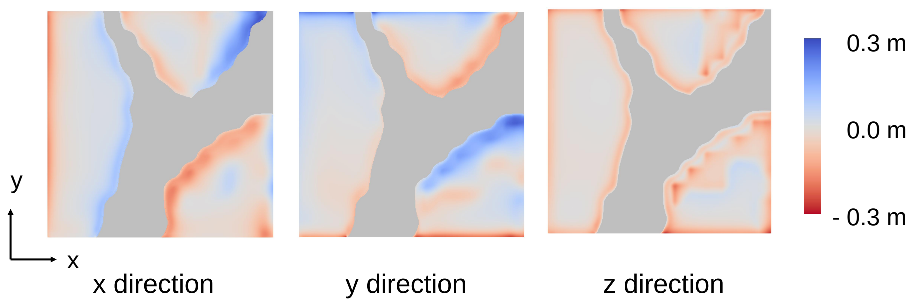

Fig. 6: Displacement on the ground surface at t =20 s in the application.

only with a slight increase in computation time compared to the previous fast analysis method [16].

4 Conclusion

In this study, we developed a stabilization method for multi-physics earthquake simulation of the digital twin. In the multi-physics simulation considering soil liquefaction, the computation instability can occur when a high spatial resolution is used. In the developed method, the constitutive law is averaged using a non-local approach. With this method, the simulation was stably performed even with a high spatial resolution of 0.125 m, and the simulation results were converged. The multi-physics earthquake simulation with a 702 million DOF soil-structure model with 0.5 m resolution was performed to show that the developed method enables us to stably perform the large-scale high-resolution analysis.

Even though the implementation of the constitutive law [11, 10] is presented in this paper, the developed method is a versatile method, and it can be applied to other constitutive laws that could cause the simulation instability. Future work involves the validation of simulation results of the developed method, the use of 3D seepage analysis for the distribution of groundwater level, and soil

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liquefaction analysis under drained conditions. Furthermore, integration with observed data using data assimilation and machine learning is expected to result in a more reliable simulation.

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