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Applicability of ROM to Seismic Response Analysis of Caisson-Type Seismically Strengthened Quay Walls against Level 2 Ground Motion

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Abstract: In the performance verification of seismically strengthened quay walls against level 2 ground motion, seismic response analysis is performed for only one or a few combinations of input variables, and the uncertainties associated with each design variable are often not taken into account. In this study, the applicability of the Reduced Order Model (ROM), which has been previously studied, to the results of 2D-FEM seismic response analysis of a caisson-type quay wall against level 2 ground motion is confirmed in order to introduce the uncertainty of each design variable in the performance verification of port structures against level 2 ground motion, and to extend the reliability-based design method to spatio-temporal analysis based on spatio-temporal distribution of each physical quantity such as displacement and hereinafter referred as to excess pore water pressure ratio (hereinafter referred as to epwpr). The results show that the predictions in ROM can accurately reproduce the response values in 2D-FEA, especially for displacement, even with a relatively small number of modes.

Keywords: Reliability-based design; Reduced Order Model; Caisson-type quay wall; 2D Seismic response analysis.

1 Background and Objectives of the Study

The necessity of this study is described here with a brief description of the recent changes in the design system of port structure code in Japan, Technical Standards for Port and Harbour Facilities in Japan.

After the 1995 Hyogo-ken Nanbu Earthquake, which caused historic damage to port structures in Japan, the 1999 edition of the port structure code (OCDI 2002) stipulates that port and harbor structures must be able to withstand level 2 ground motion. As a result, in addition to the conventional static performance verification for level 1 ground motion, the verification of response values such as residual displacement and generated cross-sectional force of port structures after an earthquake is now required by seismic response analysis for level 2 ground motion for critical facilities such as seismically strengthened quay walls. In the 2007 version of the port structure code (OCDI 2009), influenced by Eurocodes, which was the first to introduce the reliability-based design method, the Level 1 reliability-based design method (partial coefficient method), which assigns partial coefficients to individual design variables only in the performance verification for permanent and variable conditions, was introduced to allow design that takes into account the uncertainty of each design variable. Next, in the 2018 version of the port structure code (OCDI 2020), the design simplicity and feasibility of evaluating the uncertainties of individual design variables were reviewed, and one partial coefficient was assigned to each of the load and resistance (Takenobu 2019).

The above is the recent evolution of the design system of port structure code, but the authors believe that two main issues remain to be addressed.

The first issue is that in the performance verification of contingent conditions such as level 2 ground motion, due to the computational cost of seismic response analysis, the uncertainty of each design variable is not considered, and only numerical analysis is performed under deterministic conditions using one or a few combinations of input variables, and the performance verification is performed based on the results. Naturally, it's precisely in accidental conditions such as level 2 ground motion, where the impact on the structure is likely to be greater than in permanent and variable conditions, that performance verification that can account for the uncertainty of each design variable is desirable. The second issue is that the reliability-based design method only covers the entire port structure and only at a certain point in time (e.g., when the force balance condition is broken). Since structural weaknesses are spatially distributed and each physical quantity evolves in time until the structure fails due to the ever-changing seismic motion, a spatio-temporal extension of the reliability-based design method is desirable.

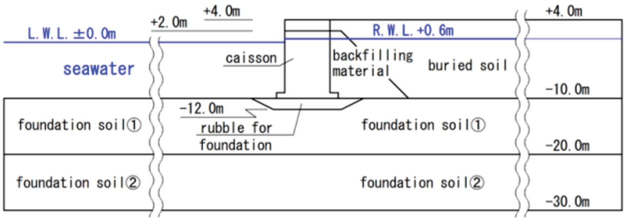


Figure 1. Analysis model cross-sectional view

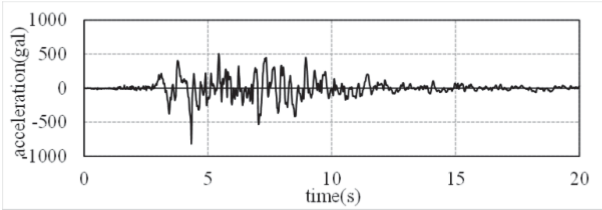


Figure 2. Input level 2 ground motion

Table 1. Estimated population of N-values

layer type	mean μ	sd σ	remarks
buried soil	10.4	3.3	Sumioka et al. (2020)
foundation soil ①	34.0	6.0	Phoon and Kulhawy (1999)

Against this background, Otake et al. (2021) proposed a reliability-based analysis method that utilizes spatio-temporal information obtained from numerical analysis of a small number of cases based on FORM, a traditional reliability-based design method (Thoft-Christensen 1982). The outline is as follows. First, the reduced order model (ROM) is constructed by computing the singular value decomposition (SVD) for a planning matrix created from the results of a numerical analysis such as 2D-FEM, constructing a basis from several left singular vectors, and performing a linear multiple regression to the input variables of the components of the projection (not an orthogonal projection) of each column of the planning matrix onto the space spanned by the basis. Next, the constructed ROM is used to obtain response variables corresponding to arbitrary input variables, and reliability-based analysis is performed by determining the time evolution of the variance of each physical quantity (e.g., displacement and hereinafter referred as to epwpr) at arbitrary points, or by determining the probability of exceeding a predetermined tolerance value for that physical quantity, through propagation analysis of the uncertainty that the input variable uncertainty has on the response variable.

With a view to introducing the proposed method in Otake et al. (2021) into the design method of seismically strengthened quay walls against level 2 ground motion in the future, this study aims to discuss the applicability of this method to the results of seismic response analysis using 2D-FEM for level 2 ground motion for caisson-type quay walls as an initial step of the introduction of the method in Otake et al. (2021). Figure 1 shows a hypothetical cross-section of the caisson-type quay wall subject to this study, and Figure 2 shows the acceleration time history of the input earthquake motion. Table 1 shows the estimated population of each soil constant used as ROM input values in this study.

2 Analytical methods used in the study

2.1 Overall structure of ROM construction and its application to uncertainty propagation analysis

Figure 3 shows a schematic diagram of the construction of ROM and its application to uncertainty propagation analysis according to Otake et al. (2021). The method consists of four phases: [Phase 1] Seismic response analysis using 2D-FEM for a small number of input variable combinations, [Phase 2] Construction of a basis for mode decomposition, [Phase 3] ROM construction, and [Phase 4] Uncertainty propagation analysis. In this study, the analysis is basically performed according to the ROM construction and its application to uncertainty propagation analysis by Otake et al. (2021), but there are some differences. In this section, we outline the construction of the ROM and its application to uncertainty propagation analysis when 2D-FEA results are used, following the flow in Figure 3, and discuss the differences in the formulation of the ROM between this study and the Otake et al. (2021). For details of the formulation, please refer to Otake et al. (2021).

2.2 Basic Theory of Analysis Methods

2.2.1 Flow of Phase 1

The results of 2D-FEA are required to construct ROM. Of the steps ① to ⑦ in Phase 1, the input data for 2D-FEA used to construct ROM are prepared in steps ① to ⑥, and the response values in 2D-FEA are obtained in ⑦. In ①, when there are Q types of soil constants used as input values in 2D-FEA, an appropriate variable transformation is applied so that the probability vector of these components follows a Q-variate normal distribution, and the mean vector $\boldsymbol{\mu}$ and variance-covariance matrix Σ are estimated pointwise. In ②, the parameters of the posterior distributions $\boldsymbol{\mu}^{\text{post}}$ and Σ^{post} are obtained by Bayesian updating of $\boldsymbol{\mu}$ and Σ using the newly obtained data of soil constants D by the survey at the analysis target. In ③, PCA (Principal Component Analysis) is used to obtain the eigenvectors of Σ^{post}, which are then arranged in columns in descending order of the corresponding eigenvalues to obtain V. In ④, V^{red} is obtained by reducing the number of columns of V while considering the magnitude of the eigenvalues in order to reduce the dimensionality of the input values. In ⑤, the design of experiment determines the total number of combinations of the principal component scores of the soil constants,

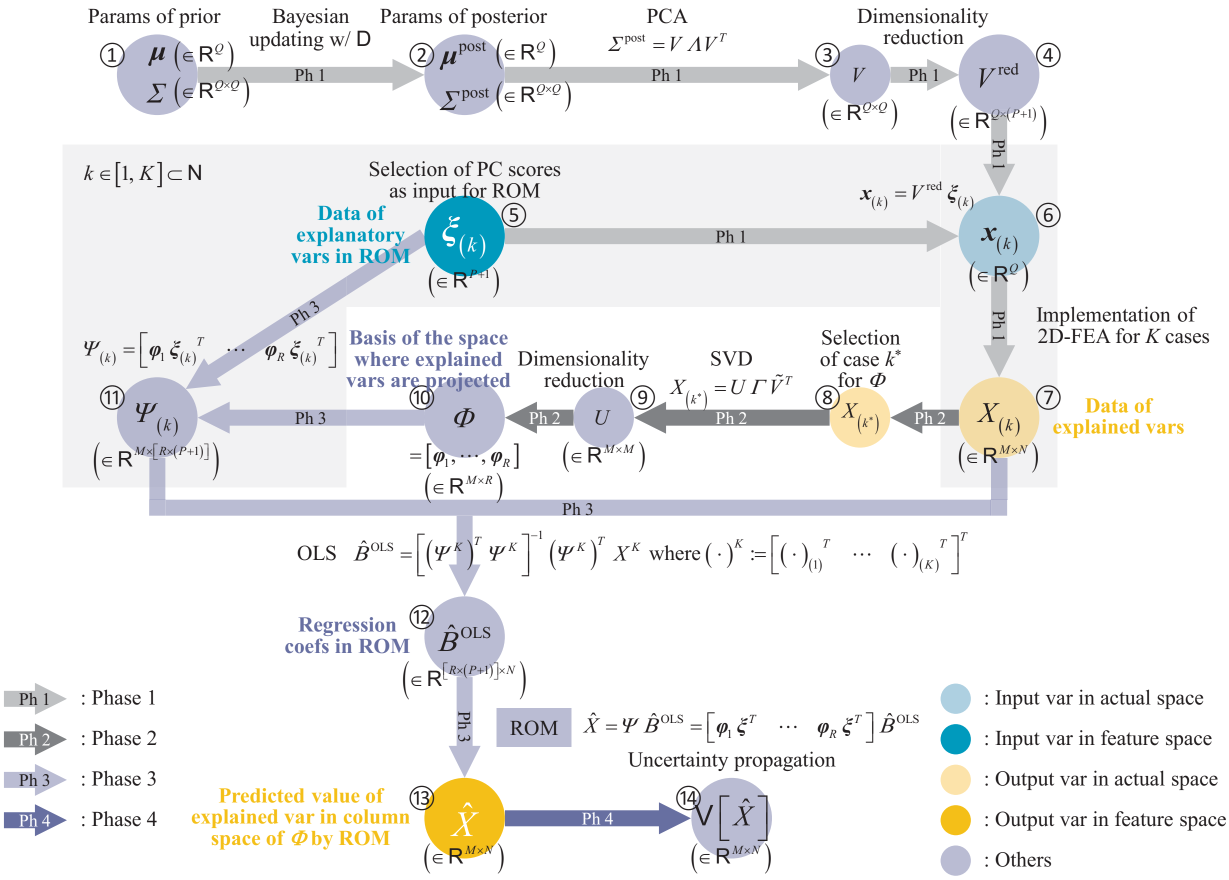


Figure 3. Flow of ROM construction and resulting uncertainty propagation analysis

K, and the combination of their values, $\xi_{(k)}$. In ⑥, the mapping of $\xi_{(k)}$ by V^{red}, i.e., the soil constants $\boldsymbol{x}_{(k)}$ before the principal component analysis of K pairs, are obtained, and this is used as the input value for 2D-FEA. In ⑦, 2D-FEA is performed with $\boldsymbol{x}_{(k)}$ as the input value, and the response value $X_{(k)}$ is obtained for each.

2.2.2 *Flow of Phase 2*

Of the steps ⑧ to ⑩ in Phase 2, in ⑧, $X_{(k^*)}$ is selected to obtain the basis to be used in ROM. In ⑨, U is obtained by arranging the left singular vectors obtained by the SVD of $X_{(k^*)}$ in the column direction in descending order of the corresponding singular values. In ⑩, Φ is obtained by reducing the number of columns of U while taking into account the magnitude of the contribution rate (Otake et al. (2021)) in order to reduce the dimensionality of the response value. This column space is the linear space to which the explained variable $\hat{X}$ in ROM belongs.

2.2.3 *Flow of Phase 3 and 4*

Of the steps ⑪ to ⑭ in Phase 3, in ⑪, the auxiliary variable $\Psi_{(k)}$ used in linear multiple regression in the ROM construction is obtained from $\xi_{(k)}$ and Φ. In ⑫, $X_{(k)}$ is linearly multiple regressed on $\Psi_{(k)}$ to obtain the regression coefficient $\hat{B}^{\mathrm{OLS}}$. In ⑬, the regression equation with $\hat{B}^{\mathrm{OLS}}$ is used to obtain the predicted value $\hat{X}$ of the response value. In Phase 4 ⑭, when ξ and $\hat{X}$ are random variables and $\hat{B}^{\mathrm{OLS}}$ is a non-stochastic variable (i.e., not a least-squares estimator but a least-squares estimate), the variance of $\hat{X}$, i.e., the uncertainty of the input variable on the response variable through ROM, is determined analytically.

2.2.4 *Differences in ROM formulation between this study and Otake et al. (2021)*

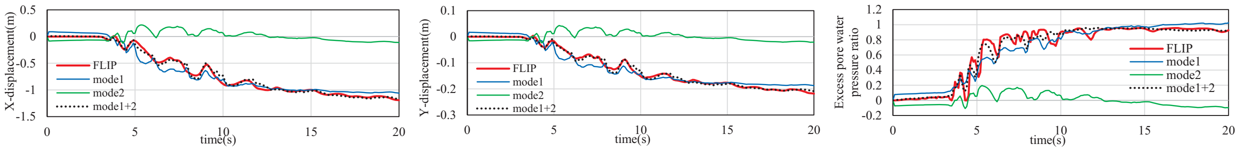
Since the data D for the soil constants newly obtained by the investigation in the analysis target is not available, $\boldsymbol{\mu}$ and Σ from the literature are used without Bayesian updating. In addition, since the number of types of soil constants used as input variables in this study is relatively small (only two), PCA is not performed in ④, and $\boldsymbol{x}_{(k)}$ is specified directly instead of $\xi_{(k)}$ in ⑥. Therefore, in ⑪, $\xi_{(k)}$ is replaced by $\boldsymbol{x}_{(k)}$ and $\Psi_{(k)}$ is obtained from $\boldsymbol{x}_{(k)}$

Table 2. Residual displacements from seismic response analysis for each analysis case

analysis case	N-value		residual disp [m]	
	buried soil	foundation soil ①	horizontal	vertical
CASE-1	$\mu-\sigma$	$\mu-\sigma$	1.743	0.351
CASE-2	$\mu-\sigma$	μ	1.287	0.225
CASE-3	$\mu-\sigma$	$\mu+\sigma$	1.066	0.174
CASE-4	μ	$\mu-\sigma$	1.590	0.306
CASE-5	μ	μ	1.194	0.219
CASE-6	μ	$\mu+\sigma$	0.993	0.166
CASE-7	$\mu+\sigma$	$\mu-\sigma$	1.188	0.274
CASE-8	$\mu+\sigma$	μ	0.832	0.154
CASE-9	$\mu+\sigma$	$\mu+\sigma$	0.678	0.119

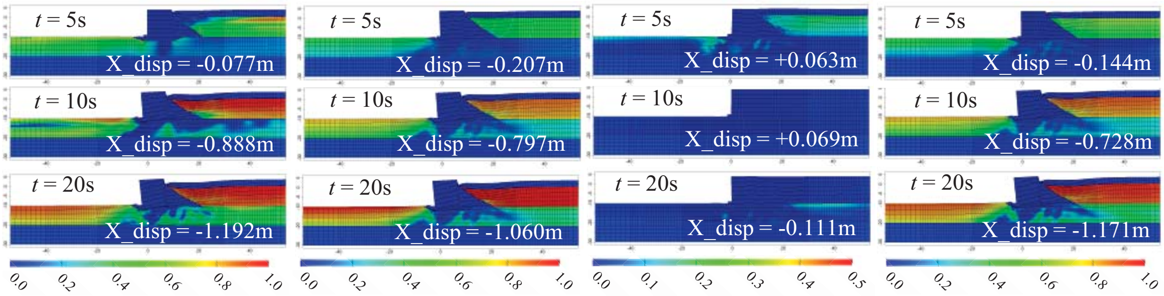
Table 3. Contribution rate and cumulative contribution rate (CASE-5)

index for mode number selection	mode				
	1	2	3	4	5
contribution rate [%]	86.80	4.40	2.00	1.70	1.20
cumulative contribution rate [%]	86.80	91.20	93.20	94.90	96.10



(a) Horizontal displacement (b) Vertical displacement (c) Epwpr

Figure 4. Time history of response values for each mode of each physical quantity



(a) FLIP (b) Mode 1 only (c) Mode 2 only (d) Superposition of mode 1 & 2

Figure 5. Snapshots at specific times for each mode (CASE-5)

and Φ .

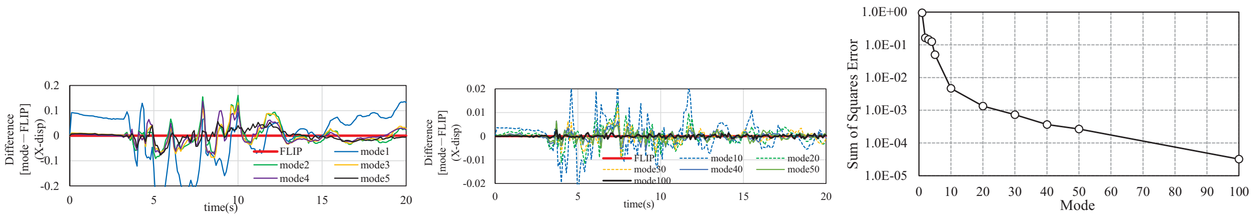
3 ROM construction for seismic response analysis of caisson-type quay wall

3.1 Analysis case of 2D seismic response analysis

In this study, the effective stress seismic response analysis software FLIP (Finite element analysis of Liquefaction Program, hereinafter called FLIP (Iai et al. (1990 a); Iai et al. (1990 b))) by 2D-FEM is used as a seismic response analysis method, which has a good track record in Japan for seismic performance verification of port structures. Both the buried soil and foundation soils ① and ② shown in Figure 1 are sandy soil beds, and the buried soil and foundation soil ① are treated as liquefiable layers, while foundation soil ② is treated as nonliquefiable layer. The analytical parameters for each soil were set using the simplified setting method (Morita et al. 1997). Table 2 shows the FEA results by FLIP used for ROM construction, showing the values at the last time step (hereafter referred to as residual values). In this study, all 9 cases in Table 2 are included.

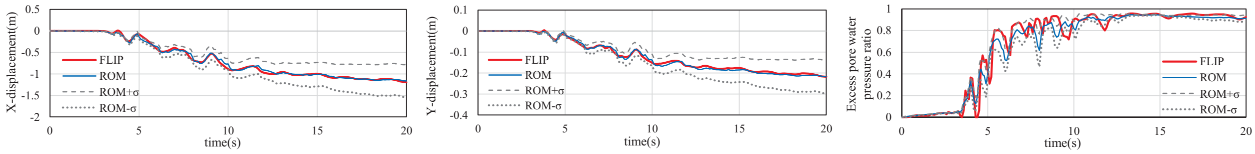
3.2 Mode decomposition and selection of number of modes

Here, among the FLIP results (see Table 2), Φ is obtained from X in CASE–5, where each input variable is the mean value, i.e., Φ from $X_{(5)}$, and use this Φ to perform linear dimensionality reduction for all 9 cases. Table 3 shows the contribution rate and cumulative contribution rate (Otake et al. (2021)) from mode 1 to mode 5. It can be seen that a large amount of information is concentrated in mode 1, and furthermore, the cumulative contribution rate exceeds 90% up to mode 2. Figure 4 shows the time histories of the response values for each physical quantity (horizontal displacement, vertical displacement, and hereinafter referred as to epwpr) for each mode. First, mode 1 consists mainly of trends such as an increase in the magnitude of displacement and an increase in the epwpr for any physical quantity, and includes some small vibration components. Secondly mode 2 has an vibration component in the time evolution of each physical quantity as its main component. Finally, focusing on the superposition of modes 1 and 2, we see that the results are generally consistent with the FLIP results for any physical quantity. Figure 5 shows a snapshot of each mode at a given time. The color contour of the snapshot



(a) Difference POD–FLIP: Modes 1 to 5 (b) Difference POD–FLIP: Modes 10 to 100 (c) SSE of the entire time history by mode

Figure 6. Difference in horizontal displacement time history b/w response values in FLIP and superposition in ROM (CASE-5)



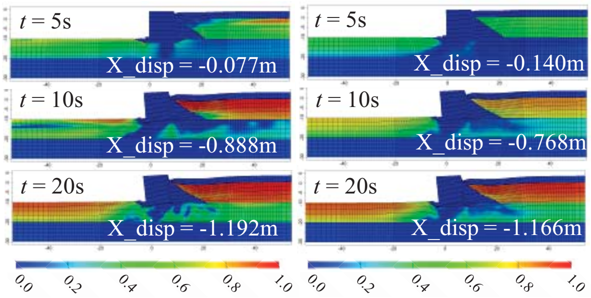
(a) Horizontal displacement (b) Vertical displacement (c) Epwpr

Figure 7. Time history response values for each physical quantity (CASE-5)

Table 4. Residual values of each physical quantity

physical quantity	FLIP (CASE-5)	ROM* (CASE-5)	ROM / FLIP [%]
horizontal disp [m]	1.192	1.166 [−0.026]	97.84
vertical disp [m]	0.218	0.218 [−0.0001]	100.06
epwpr	0.925	0.915 [−0.010]	98.88

* In square blackets are differences ROM – FLIP.



(a) FLIP (b) ROM (superposition of mode 1 & 2)

Figure 8. Snapshots of residual values (CASE-5)

shows the epwpr. First, focusing on the spatial distribution of the mode 1 response shown in Figure 5 (b), the displacement and epwpr at each time step generally agree with the FLIP results shown in Figure 5 (a). Mode 2, shown in Figure 5 (c), shows an increase in the epwpr over the entire buried soil area at t = 5 [s].

Here, in Figures 4 and 5, we focused our discussion on up to mode 2, but in design practice, it's necessary to determine which mode to extract. The basic approach in selecting the number of modes to be targeted in the ROM construction in the next section is described below.

Figure 6 shows the difference between the FLIP results and mode decomposition (Figure 6 (a) and (b)) and the sum-of-squares error (hereinafter referred to as SSE) at all time steps (Figure 6 (c)) for horizontal displacements. The time histories of the mode decomposition results shown here are superimposed on the results from mode 1 to mode 5 (Figure 6 (a)) and from mode 1 to mode 100 (Figure 6 (b)), respectively, in the order of the upper modes. So, for example, mode 5 in Figure 6 represents the superposition of the time histories of the 5 response values from mode 1 to mode 5. The results show that for the entire time history, the deviation from the FLIP results is large for mode 1 only, while the superposition from mode 2 to mode 5 shows a significant improvement. The discrepancy between the two is gradually improving as the number of superimposed modes is increased. Figure 6 (c) shows that the SSE for the entire time history is significantly reduced for superimpositions up to mode 2 compared to mode 1 alone, but the degree of reduction in the SSE when the number of modes to be superimposed is further increased is small compared to the reduction for superimpositions up to mode 2. In practical design, it's desirable to select the minimum number of modes necessary, taking into consideration the nature of the target problem, the purpose of the analysis, the nodes, elements, and physical quantities to be focused on, and the required estimation accuracy.

In the construction of the ROM for the caisson-type quay wall in this study, only the superposition of modes 1 and 2 obtained by mode decomposition is treated as the object of analysis. The reasons are as follows. In seismic performance verification, performance verification is often performed for residual values such as displacement, etc. From this perspective, it's sufficient to construct the ROM using only mode 1. However, there are some verification items, such as the relative displacement of container crane rails, which aren't dealt with in this study, that require attention not only to the residual values but also to the time history of displacement during vibration. The information of mode 2, which represents a vibration component of a few 10 [cm] in the time history, is also extremely important. On the other hand, as shown in Figure 6, further increasing the number of mode selections is beneficial to improve the accuracy of ROM estimation, but the number of mode selections should be kept to the minimum necessary for easy processing of the analysis data. For these reasons, only the superpositions of modes 1 and 2 were included in the analysis in this study.

3.3 ROM construction

Here, we use the 9-case FLIP results shown in Table 2 and construct the ROM with the number of modes set to 2. The validity of the ROM is tested by comparing the FLIP results with the predictions in the ROM using the input values for case CASE-5, where each input variable is the mean value. Table 4 shows the results of the comparison between the response values in FLIP and the predictions in ROM. For all physical quantities, the predictions in ROM accurately reproduce the response values in FLIP. Figure 7 shows the time history of response values at FLIP and predicted values at ROM. Figure 8 also shows snapshots at key time steps. The spatiotemporal distribution of each response value shows that the predicted values in ROM generally reproduce the response values in FLIP. Looking at the epwpr (e.g., t = 10 [s] in Figure 8), the predictions in the ROM are slightly underrepresented relative to the response values in the FLIP, but since this study is mainly concerned with performance verification examples for displacement, the predictions in the ROM are sufficiently reproducible for displacement relative to FLIP results, and the ROM constructed in this chapter is deemed appropriate to apply. However, as mentioned above, in practical design, the number of modes should be selected according to the nature of the target problem, the purpose of the analysis, and the required estimation accuracy. For example, to accurately predict the time history of response values during vibration in ROM, it's effective to increase the number of modes to be covered, as shown in Figure 6.

4 Conclusions and Future Issues

In this study, the method proposed by Otake et al (2021) which is a reliability analysis method that maximizes the use of spatio-temporal information obtained from numerical analysis, is applied to the problem of earthquake response analysis of a caisson-type quay wall against level 2 ground motion.

The conclusions of this study are as follows.

- When the surface soil consists of two layers and the N-values of each layer are assumed to be random variables, as in the present problem set-up, the ROM constructed from 9-case calculations can accurately reproduce the response values in FLIP for displacement by superposition up to mode 2.
- To accurately predict the time history of displacement during vibration in ROM, it is effective to increase the number of modes. However, as the number of modes is increased, the accuracy of reproducing the response values in FLIP based on the predictions in ROM improves up to a certain point, but no significant improvement in reproduction accuracy is seen even if the number of modes is increased beyond that point.
- For the epwpr, the accuracy of reproducing the response values in FLIP based on the predictions in ROM is not as high as for displacement.

The following issues are expected to be addressed in the future.

- Improvement of prediction accuracy of epwpr by ROM for prediction of liquefaction location and liquefaction start time
- Extension of this method to cases where linear multiple regression is not applicable, such as ROM construction for seismic motions with component waves that have greater impact on port structures, and application of this method to other structural types such as sheet pile moorings
- Calculation of reliability indices and spatio-temporal distribution of failure probability by this method, and development of design method for port structures based on them

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