IASMiRT

SMiRT 26
50 Anniversary Berlin/Potsdam

Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division Ⅲ

PROPOSAL OF VALIDATION PROCEDURE OF NON-LINEAR SEISMIC RESPONSE ANALYSIS METHOD

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ABSTRACT

Basic idea and the procedure to validate the analysis model and the method by use of the non-linear seismic response analysis are proposed. The procedure of validation consists of two stages. First stage is to confirm the linear behavior. Second stage is to confirm the non-linear behavior. At each stage, the reproducibility as the degree of accuracy and the predictability as the degree of variation are estimated based on the simulation to some analysis models which considered uncertainty.

Validation of one-dimensional model of ground is carried out by using the seismic analysis code DYNES3D as the example. Considering the uncertainty of the ground model and the nonlinear properties of soil, the reproducibility of the simulation is evaluated by comparing the numerical analysis results with the observation. Furthermore, the predictability is also evaluated. The method to evaluate the degree of accuracy and to choose the best estimate model is successfully obtained.

INTRODUCTION

After the 1995 Southern Hyogo Prefecture Earthquake, the standards about the earthquake-resistant design of various infrastructures were revised to the frame which utilizes non-linear earthquake response analysis, but the frame to guarantee precision of the nonlinear earthquake response analysis has not been presented. ASME(2007), JSCES(2015) and AESJ(2015) made the society standard about verification and validation of the numerical analysis, and have carried out the approach about the reliability for the engineering simulation as well as the quality assurance. It is important to establish the frame to improve the quality and reliability in order to promote the use of the numerical analysis to the design and the evaluation of the complicated phenomenon (e.g. dynamic behavior of infrastructure) as well as the development of the technique such as the particle method that can evaluate a more complicated behavior.

Above-mentioned standards are divided into two approaches. One is named as model V&V and is the approach about verification and validation of the analysis model based on the evaluated accuracy considering uncertainty. Other one is the approach about the quality assurance of the simulation. The objective of this paper is the systematization about the validation procedure for the non-linear analysis of the ground and the structures at a point of view called ‘model V&V’. At first, the basic idea about the implementation procedure for 'model V&V' of not only the analysis code but also the analysis model which is the input information is described based on the guideline specified by Japan Society of Civil Engineering. Next, the object behavior is a non-linear of the ground during earthquake. And the object code is the one-dimensional non-linear earthquake response analysis code「DYNES3D」, Yoshida (2004), in time domain. The code is coded by Yoshida based on the assumption that the ground structure is horizontally layered structure. The object of the validation is Tokyo Bay reclaimed land which has the related information such as the ground structure, Masda et al. (2001), the material properties of soil, Yoshida et al. (1994) and seismic observation data with vertical array, Annaka et al. (1994).

BASIC IDEA AND PROCEDURE OF VALIDATION

Basic idea

At first, the object of the numerical analysis is the behavior to collapse from deformation of the ground for various action, the response behavior of the ground - structure. Depending on the method of the design and the evaluation for those behavior, it will obtain the indeed result by the numerical analysis for the analysis model including various dimensional ground and structures. The input information including the overall shape image of target is necessary for the simulation by using the analysis code and becomes the analysis model.

There is the approach of the validation of the analysis model on the basis idea of model V&V specified by ASME, but is on the basis of a procedure as the flow shown in Figure.1 because the target of the simulation is the system which has the strong nonlinearity behavior such as the ground and structure materials. At first, the objective behavior is expressed as the concept model of the mechanical system for its intended use. The concept model is expressed as the idealized mathematical model based on the mechanical model of the objective behavior. The mathematical model is expressed as a model implemented as a computational model by a digital computer. Verification is the implementation process which confirms that the computational model mounted on analysis code expresses faithfully the mathematical model as the basis and leads a solution of the computational model in the range of the performance of the digital computer. In addition, based on the results obtained by the simulation of the analysis model by using the verified analysis code, the validation is to confirm that the reproducibility and the predictability satisfy the criterion of the intended use.

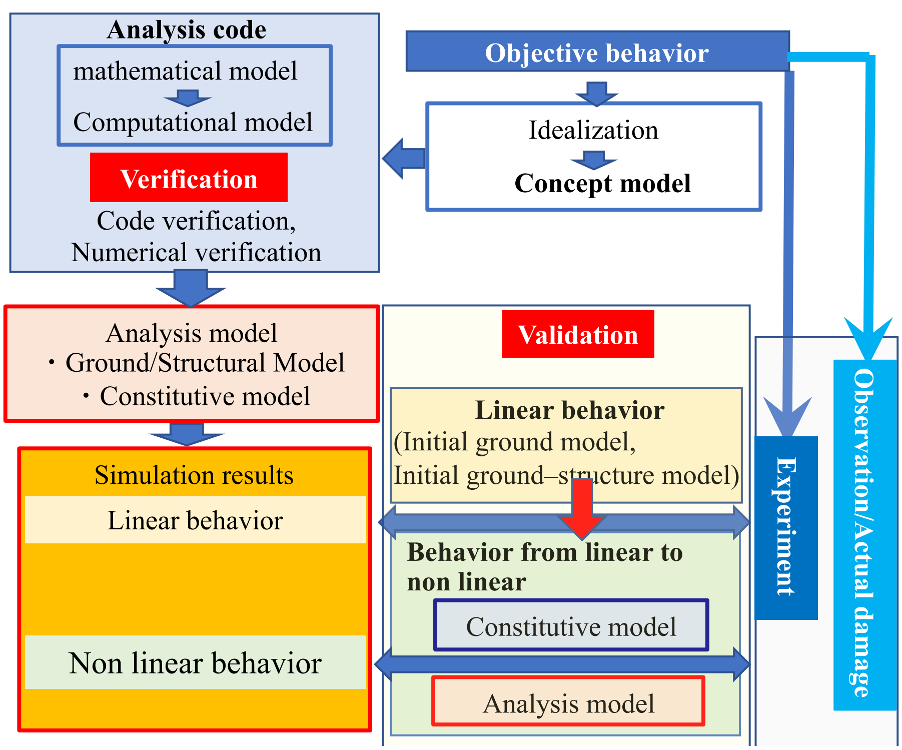


Figure 1. Flow of implementation procedure of verification and validation

The reproducibility is the degree of the accuracy about the evaluation index obtained by the comparison between the simulation of the analysis model in consideration of uncertainty and not only the existing observation but also the laboratory test. The predictability expresses the degree of variation of the evaluation index of the simulation result under the condition which is different from the condition that the reproducibility was confirmed. As for the different condition, different shape of structure, different applied action, structural system whose member is the different structure from the target structure etc. can be considered. For example, as the influence of the uncertainty of the model on the simulation result in the strong nonlinearity domain, the presence of the instability, e.g., the change of the extreme value is confirmed.

This approach of V&V is based on the concept of model V&V specified in ASME V10, but the procedure of the validation consists of two stages as the flow shown in Figure 1 because a main target of the standard of ASME is equipment, but a structural system with the material in which strong nonlinear behavior appears is the target of the simulation in this approach. As shown in the flow of Figure.1, the validation of the initial analysis model whose material behaves linear is carried out at the first stage. At next stage, validation of the analysis model is carried out by the simulation that the material property behaves to nonlinear from linear.

Evaluation index and metric of evaluation

Among the characteristic values of response obtained by simulation of analysis model to confirm reproducibility and predictability, physical quantity which is necessary to evaluate not only degree of the accuracy but also the degree of variation is named as the evaluation index. Furthermore, the criteria to evaluate the degree of the accuracy quantitatively is named as the metric of evaluation.

In the guidelines of ASME, two approaches are described to evaluate the degree of accuracy. In both approaches, M^{SQR} shown in equation (1) is used as the metric of evaluation. Hence, SQR expresses system quality of response. In Approach2 which is used when there is some experimental data, M^{SQR} is evaluated by using equation (1) which considers not only the uncertainty of the experimental data but also the uncertainty of the analysis model based on the simulation result. Hence, M^{SQR} represents the average of the relative error exactly. Here, $F_{SQR^{sym}}(y)$, $F_{SQR^{exp}}(y)$ are the cumulative distribution function of the simulation result about the evaluation index y and that of the experiment about the evaluation index y respectively. $|SQR^{exp}|$ expresses the mean of the experimental value.

$$M^{SQR} = \frac{1}{\left|\overline{\overline{SQR}}^{exp}\right|}\int_{-\infty}^{\infty}\left|F_{SQR^{sym}}(y) - F_{SQR^{exp}}(y)\right|dy \qquad (1)$$

The differences shown in equation (1) between existing observation, laboratory test and simulation result of the analysis model is considered as the estimated error Δ_{model} obtained by the analysis model. Here, in term of the evaluation index Y, the difference between the simulation result Y_{sim} and the observation Y_{Obs} (or the laboratory test Y_{Exp}) is able to express as shown in equation (2). Here, δ_{sim} and $\delta_{Obs/Exp}$ represent the difference of the true value to the simulation result and the difference of the true value to the observation (or laboratory test) respectively. The latter is mainly caused by the measurement errors of observation (or experiment), and, by assuming that the observation data is the true value by the reason why the difference value is very small, Δ model can consider as δ_{model} expressing the uncertainty of the model as shown in equation (2).

$$\Delta_{model} = Y_{Sim} - Y_{Obs/Exp} = \delta_{Sim} - \delta_{Obs/Exp} \fallingdotseq \delta_{model} \tag{2}$$

Then it is thought that not only the metric provided by ASME but also the metric to express the relative error such as the ratio of an estimate error to an observation data and the ratio of a simulation result to observation data are useful as an metric of evaluation standard (M^{RQ}: Metrics of Response Quality).

$$M_{RQ}=\Delta_{model}/Y_{Obs/Exp} \; or \; =Y_{Sim}/Y_{Exp} \tag{3}$$

Procedure of validation

The procedure of validation divides the object behavior into two stages as shown in Figure 1 and carries each stage out. Here, the objective by the validation for the linear behavior is to evaluate the reproducibility and to set the initial analysis models to be reliable. The reliable analysis model is the initial analysis model which is appropriate reproducibility among the models which consider the uncertainty of the fundamental properties such as the elastic modulus and the ground structure of elastic wave velocity etc., and is named as the most suitable analysis model. Next, by the validation for the behavior of the material property to reach the non-linear level from linear, the most suitable analysis model is uses as the basic information of the analysis model. Carrying out the reproducible confirmation of the analysis mode considering the uncertainty of the constitution model of materials properties with the parameter, setting the most accurate model become the purpose as well as the predictability conformation. On the reproducible confirmation, the analysis model having appropriate predictability among the analysis models in consideration of the uncertainty such as the parameters of the constitution model is named as the best estimate model.

OUTLINE OF OBSERVATION EARTHQUAKE TO USE FOR VALIDATION AND GROUND CONDITION

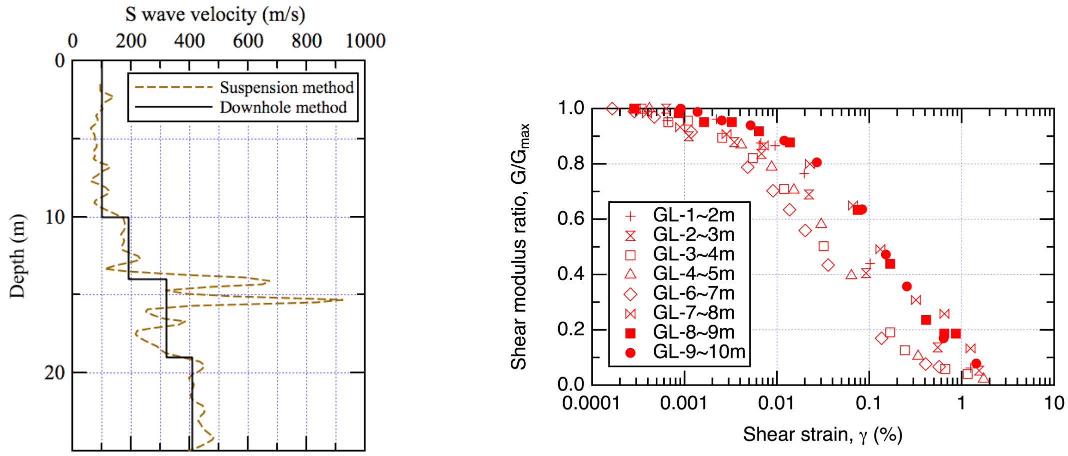
Here, the seismic records obtained by the seismic observation that the vertical array of the seismographs was arranged in reclaimed land in Tokyo Bay are used as well as the detailed ground survey data. As for the vertical array observation, the four seismographs were installed in the depth direction GL-1.5m, -22.3m, -38.5m, -80.0m from the surface of ground. During the observation period, 16 earthquakes including the 1987 Chiba east offshore earthquake (Mj=6.7) were observed. Because the distribution of the epicenter position. did not have large bias, and a record with the unique value was not confirmed, all observation records were used for the validation.

In addition, as the ground survey such as PS logging test, down hole method and suspension method were carried out at a location about 40m away from the seismic observation point. As for the comparison of S wave velocities obtained by both methods as shown in Figure 2 a), the value is remarkably different at between GL-14m and GL-16m. At the depth, N value is large value which is from 30 to 40, and the change of the S wave velocity obtained by the suspension method correspond with the change of N value in the local ground. Furthermore, the dynamic deformation characteristics tests to evaluate the non-linear characteristic of the material properties of soils have been obtained every 1.0m in the depth as shown the example in Figure 2 b).

UNCERTAINTY FOR MODELING ANALYSIS MODEL AND EVALUATION INDEX

For validation, the model of ground is used as the target analysis model for modeling the range from the surface of ground to GL-23m by considering the depth where the seismographs are installed.

In order to make an analysis model, two characteristics which are well known are considered as major uncertainty factors of ground. One is S wave velocity structure of the ground. Other one is the



a) S wave velocity structures b) relationship between shear modulus ratio and shear strain

Figure 2. Comparison of S wave velocity structures by two methods and relationship between shear modulus ratio and shear strain

constitution model about materials properties. Other characteristics, e.g., the unit volume weight, are assumed to be the fixed values. As for observed 16 earthquakes during the seismic observation, the seismic records whose maximum accelerations were from 10gal to more than 100gal were obtained. Those records are used for evaluating the reproducibility as well as for using as the input earthquake ground motion.

As for the evaluation index to use for the reproducible evaluation, various indexes are selected based on the current status about the various utilization of simulation results such as earthquake resistance design. First of all, peak ground acceleration (PGA) to use for evaluations such as the design seismic intensity at the ground surface, peak ground velocity (PGV) which is associated with the seismic intensity and Alias intensity (AI) related to the energy of the seismic ground motion are employed as the index about the maximum value of earthquake ground motion named as the maximum index. Next, the spectrum intensity (SI) which is the scalar index of the spectrum characteristics related to geotechnical disaster, the spectrum amplitude at the specified period e.g. the period of first mode and the period of third mode etc., are employed as the direct index about the frequency characteristics of earthquake ground motion named as the frequency index.

As the reproducibility of those evaluation indexes, $M^{SQR}$of by ASME and M^{RQ} which is the ratio of the response to the observation are used as the evaluation metric.

VALIDATION OF INITIAL ANALYSIS MODEL FOR LINEAR BEHAVIOR

Setting initial model considering uncertainty

As shown in Figure 2., the ground structure of S wave velocity at the object site greatly varied according to the exploration methods. Then the three models are used for the first step of the validation as the initial ground models. S wave velocity structure obtained by down Hole method is named as G_model 1. And S wave velocity structure obtained at every same 20cm by the suspension method is G_model 3. S wave velocity structure that averaged its local change were used as G_model 2. Furthermore, the initial ground model (G_model 4) is not the model based on the ground survey, but is added to the model of S wave velocity. The structure was the model identified by Annak et al.(1994) based on the seismic records whose maximum acceleration are small.

The comparison of distribution of S wave velocity for each initial model is shown in Figure 3. The comparison of frequency response function for each initial model is shown in Figure 4. Thickness of layer of initial ground model except G_model 3 is 1.0m. By focusing attention to the first natural frequency of each initial ground model, the value for G_model 1 is 0.47 seconds and the value for G_model 4 is 0.58 seconds. Then it is found that the difference between those values is more than 0.1 seconds.

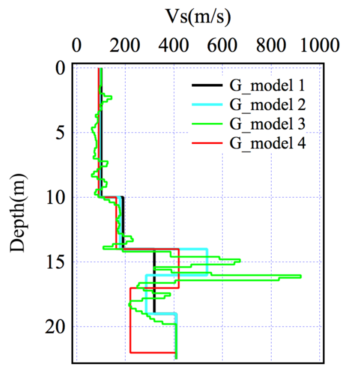


Figure 3. Comparison of S wave velocity structures of 4 initial structure models

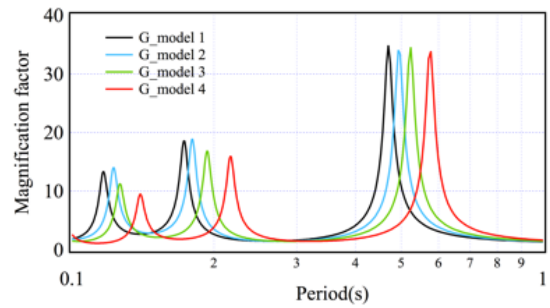


Figure 4. Comparison of frequency response function of 4 initial structure models

Confirmation of Reproducibility and Most suitable model

At a point of view that behavior in the ground can consider to be a linear range, the reproducibility is confirmed by using the record of 12 earthquakes that maximum acceleration observed on the ground surface becomes less than 40Gal. In addition, the input earthquake ground motion in each earthquake acted as composition wave (E+F) as a career at the acceleration time of the ingredient of the direction where maximum acceleration was provided during an observation record in underground GL-22.3m. In addition, the acceleration time of the direction where maximum acceleration was observed at GL-22.3m is used as the input earthquake ground motion in each earthquake and acted as compound wave (E+F). The maximum shear strain obtained by the response analysis to each model gave becomes maximum value around the GL-10m, and the value is from 5 x 10^{-4} to 10^{-4}. Based on the reduction rate of the shear modulus estimated by the test results about the shear deformation characteristics of the ground materials, the reproducibility is considered to be able to evaluate by using the response properties of the ground obtained by the linear response analysis against 12 earthquakes.

In order to evaluate the reproducibility quantitatively based on the maximum index and the frequency index obtained by the simulation, M^{SRQ} and M^{RQ} are calculated and are shown in Table 1. As an example of M^{SRQ} about the evaluation index PGV, the cumulative distribution function calculated by the simulation results against 12 earthquakes for each initial ground model is shown in Figure 5 together with the cumulative distribution function calculated by the observation records. The cumulative distribution function of the calculation value and the observation value is modelled as a lognormal distribution respectively. Here, the characteristics values such as a median and a logarithm standard deviation are calculated by using the calculation value and the observation value. The mean and coefficient of variance are shown in parenthesis of the table about the letter metric of evaluation. In addition, M^{SRQ} in the table is doing a hatch with a different color (in the turn of light blue and yellowish green) in the small turn of the value as well as the mean of ratio in the turn near 1.0.

From a viewpoint of the accuracy, as for three evaluation indexes of PGA, PGV and SI, value of each M^{SRQ} for the initial ground model 4 (G_model 4) is less than 10% and values of each M^{RQ} is near 1.0. Then the initial ground model 4(G_model 4) is considered to be quite accurate. As for the initial ground model 3 (G_model 3), the evaluation metric of PGA, PGV and SI becomes the value that seems to be accurate next to initial ground model 4 (G_model 4). Based on the above, by evaluating the metric of evaluation for each evaluation index generally, the initial ground model 4 (G_model 4) obtained by identification is seemed to be the most suitable analysis model that the characteristic of the earthquake ground motion at the ground surface can be reproduced the most accurately. As there are not many points where such identified ground model is provided, the initial ground model 3 (G_model 3) is considered to be the second best model. However, the initial ground model 4 (G_model 4) is used for the validation of the analysis model of the non-linear behavior as the most suitable analysis model reproducing the linear behavior.

Table 1: Comparison of evaluation metrics for each evaluation Index of each initial structure model

Evaluation Index	Evaluation Metric	Ground structure model of shear wave velocity			
		G_Model 1	G_Model 2	G_Model 3	G_Model 4
PGA	M^{SQR}	0.71	0.39	0.11	0.08
	M^{RQ}	1.70(0.33)	1.37(0.24)	1.12(0.25)	1.09(0.27)
PGV	M^{SQR}	0.29	0.07	0.09	0.02
	M^{RQ}	1.47(0.35)	1.18(0.25)	1.14(0.21)	1.11(0.20)
AI	M^{SQR}	1.72	1.04	0.74	0.81
	M^{RQ}	8.07(1.36)	4.30(0.83)	2.61(0.31)	2.88(0.43)
SI	M^{SQR}	0.16	0.08	0.08	0.06
	M^{RQ}	1.53(0.35)	1.24(0.21)	1.20(0.21)	1.18(0.18)
SV1	M^{SQR}	2.13	2.01	1.24	1.39
	M^{RQ}	2.57(0.35)	2.43(0.36)	1.44(0.28)	1.59(0.27)
SV2	M^{SQR}	2.48	2.46	2.44	2.42
	M^{RQ}	1.22(0.35)	1.01(0.32)	0.78(0.32)	0.63(0.37)

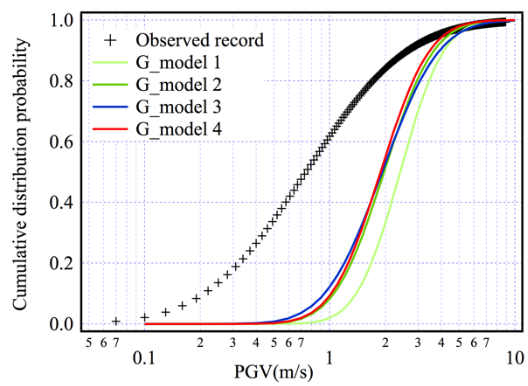


Figure 5. Comparison of cumulative distribution functions

VALIDATION OF THE ANALYSIS MODEL FOR LINEAR AND NON-LINEAR BEHAVIOR

As for the validation of the analysis model by confirming the reproducibility and the predictability, the most suitable analysis model (G_model 4) obtained in the previous chapters is used as the fundamental model of the ground structure and the material property. 4 earthquakes except 12 earthquakes which are used in the validation of linear behavior are used. In addition, six evaluation indexes same as the previous chapter is also used.

At first, the reproducibility about the non-linear behavior of the material property is confirmed by considering the uncertainty caused by the constitutive model. Here, because the results of the shear deformation characteristics are obtained, 3 constitutive models, HD model (HD_model), RO model (RO_model) and Yoshida model (YN_model), are used to consider the uncertainty. HD_model and RO_model are numerical formula model. The parameters of each constitution model are determined based on the shear deformation characteristics of the material obtained at the object site. As the evaluation index to evaluate the reproducibility of the constitutive model, the shear modulus ratio (G/Go) and the damping constant (h) that were obtained by the shear deformation test were used. The relative error into which the difference of the experimental value to the value estimated by the constitutive model is divided by the experimental value is used as the evaluation metric. About HD model and the RO model, the relationships between the relative error and shear strain are shown in Figure 6. About HD model, the relation between G/Go and the shear strain is seemed reappear to some extent. However, the difference from the experimental value is recognized about the damping constant. In addition, the reproducibility of RO_model is found not to be good.

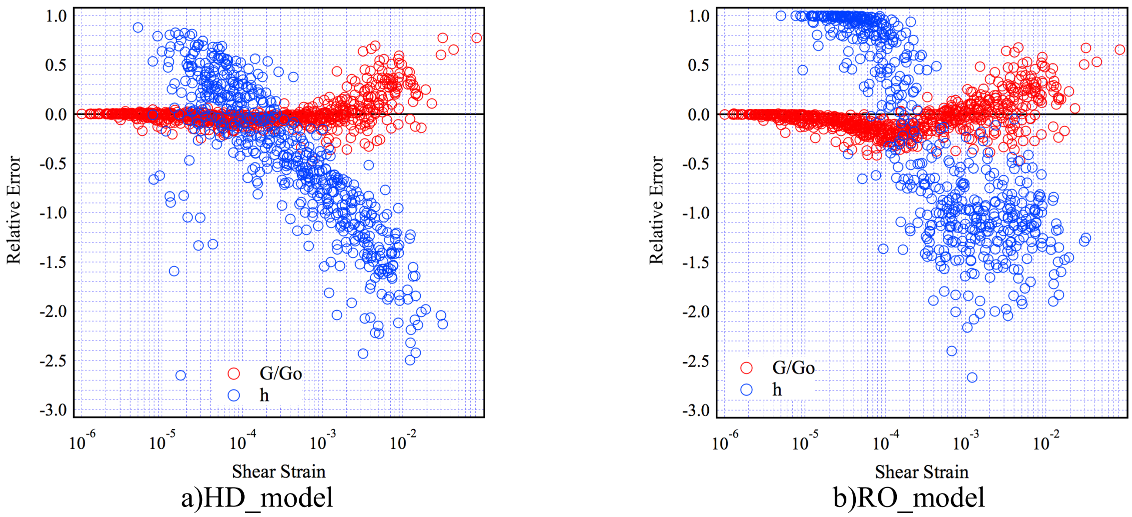


Figure 6 Relationships between the relative error (G/Go, h) and and shear strain

Then, using the analysis model that considered three constitutive models as uncertainty, the reproducibility is evaluated quantitatively. Two evaluation metrics (M^{SRQ}, M^{RQ}) were calculated as well as the evaluation of the linear behavior and is shown in Table 2. About M^{RQ}, only the mean is shown in Table 2. In addition, not only the frame of the value that M^{SRQ} is minimized but also the frame that M^{RQ} is almost 1.0 were painted blue. M^{SQR} of RO_model is minimized in the evaluation index that are PGA, PGV, SI and velocity response spectrum at first mode (SV_1). And M^{SQR} of the Yoshida model is minimized in the evaluation index that are AI and SV1. And M^{RQ} of the model is minimized in the evaluation index that are PGA, PGV, SI and SV1. As for the analysis model who used the ground structured model with S wave velocity structure provided by identification, Yoshida model as a constitution model, it is found that it is the best estimate model to be able to reproduce in the observed record most by the seismic observation in the object site. As for the RO model among the constitution models, the value of metric evaluation M^{SRQ} for PGA, PGV, SI and the velocity response spectrum at the period of first mode was minimized. As for Yoshida model, the value of Ratio about PGA, PGV became smallest as well as that of the velocity response spectrum at the period of first mode. Furthermore, the value of M^{SRQ} about AI became smallest as well as that of the velocity response spectrum at the period of first mode. As the best estimate model which is the analysis model to be able to reproduce the observed record best at the object site, it is found that the S-wave velocity structure is the model identified based on the seismic records, and that constitutive model is Yoshida model.

Finally, using the best estimate model, the predictability is evaluated based on the sensitivity analysis of the surface ground response against the larger intensity earthquake ground motion as the different condition from the condition to evaluate the reproducibility. 17 seismic records observed in 12 earthquakes which caused disaster were used. Those earthquakes were chosen based on not only the different record characteristics such as the frequency characteristics and duration time but also the different source characteristics such as inter-plate earthquake and inland earthquake. Those records act on the base layer of the best estimate model as the incident wave. And PGA and PGV at the ground surface obtained by the simulation are focused on as the response characteristics. The maximum amplitude (2E) of the input wave was adjusted in 100Gal, 300Gal, 500Gal and 700Gal. Depending on the frequency characteristics of the input wave, the response values such as PGA and PGV are seemed to be scattered. However, appropriate predictability was able to be confirmed because an inappropriate analysis result was not obtained as well as that being tendency of the general non-linear response.

Table 2: Comparison of evaluation metrics for each evaluation index of each analysis model

Evaluation Index	Evaluation Metrics	Non-linear model		
		HD-model	RO-model	YN-model
PGA	M^{SQR}	0.32	0.10	0.26
	M^{RQ}	0.69	0.65	0.74
PGV	M^{SQR}	0.16	0.03	0.05
	M^{RQ}	0.86	0.58	0.92
AI	M^{SQR}	0.08	0.07	0.04
	M^{RQ}	0.89	1.39	1.23
SI	M^{SQR}	0.18	0.01	0.07
	M^{RQ}	0.85	0.56	0.91
SV(T1)	M^{SQR}	0.05	0.02	0.02
	M^{RQ}	0.90	0.64	1.02
SV(T2)	M^{SQR}	0.07	0.09	0.00
	M^{RQ}	0.83	0.97	1.04

CONCLUSION

Basic idea and procedure for validating not only non-linear seismic response analysis code for ground and structure but also analysis model was described. In addition, the case study was also described. Validation processes are carried out at 2 stages. At each stage, predicted performance as the degree of variation and reproducibility as the degree of accuracy was estimated based on the results of the analysis to some analysis models who considered uncertainty. Setting the best estimate model at the point of the reproducibility is seemed to be the significance of V&V as well as the quantitative evaluation of the accuracy. An administrator of the analysis to utilize numerical results for a design and an evaluation will judge the applicability of an analysis cord and the analysis model depending on a use.

The result obtained by assuming the ground to be the one-dimensional model which was horizontal layer was indicated in the evaluation example of validation. In addition, one-dimensional non-linear earthquake response analysis code, "DYNES3D", in the time domain coded by Yoshida (2004) is used for validation. The intensity of the observed earthquake ground motion is not so large, but it is found that the accuracy to estimate the evaluation index of the observed is evaluated within the range of around 26% from 0 by using the best estimate model as the analysis model in the non-linear behavior.

ACKNOWLEDGMENTS

We are grateful to the subcommittee members of study of systematization on verification and validation about non-linear earthquake response analysis code of ground and structure for helpful discussions and comments on the manuscript.

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