Preliminary Numerical Evaluation of High Acceleration Seismic Test Using Discrete Element Model 3D-RBSM

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1. Introduction

In general, seismic fragility evaluation of the seawater pipe duct carrying cooling water for the nuclear power plants is regulated by the limits imposed on the inter-story drift angle of the box culvert strcuture[1)]. However, limit of fragility evaluation should be defined as per the ability of the seawater pipe duct to carry cooling water as a boundary. Therefore, to establish a fragility evaluation method based on coupling of structure and equipment, we are conducting advanced research on both seawater pipe duct (civil engineering) fragility and piping (equipment) fragility. In addition, headed anchor bolts (anchors) are generally used to fix the piping equipment to structure. And, for the evaluation of coupling between structure and equipment including anchors, it is common to evaluate each of them individually. In this regard, to establish a preliminary numerical study on fragility evaluation method considering coupling of structure and equipment based on experimental study, we used a discrete element model named Three-Dimensional Rigid Body Spring Model (3D-RBSM)[2)] that is capable to evaluate detailed behavior of the coupled system including the boundaries.

Fig. 1 Outline of test specimen

2. Outline of Testing and Numerical Model

To perform experimental study, a reinforced concrete box culvert (Fig. 1) with a scale of about 1/2~1/3 of actual structure was constructed to be easily mounted on a shaking table available at the Central Research Institute of Electric Power Industry (CRIEPI). Box culvert was designed to fail in bending. Fig. 2 shows the reinforcement arrangement in box culvert. Design strength of concrete and rebar were 24MPa and 290MPa respectively. A weight of 2.093t (0.0218MPa) was imposed at the top of box culvert to apply the inertial forces due to the seismic motion induced by shaking table. In addition, accelerometer and displacement meter were installed at the top of box culvert to measure horizontal acceleration and horizontal displacement respectively.

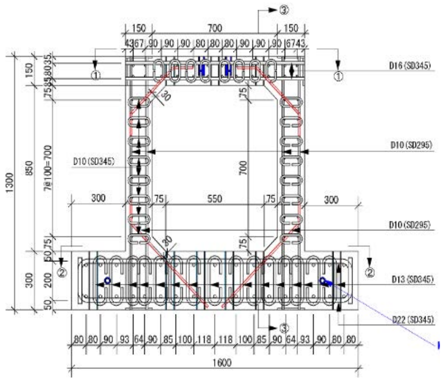

Fig. 2 Rebar arrangement in Test

To conduct numerical evaluation, 3D-RBSM was used[2)]. In this method, concrete is modelled as an assemblage of rigid particles connected by the springs at their boundary surfaces, whereas, rebar is modelled by beam elements connected to concrete mesh elements by zero-size link elements (Fig. 3). An analytical model of test specimen is shown in Fig. 4 (mesh size: 25mm). Width of analytical model is 200mm (1/4 scale of test specimen). Initial stress (0.0218MPa) is applied by forming top load plate. Afterwards, lateral displacement (pushover) is applied by forming side load plates. Fig. 5 shows the reinforcement arrangement in the numerical model.

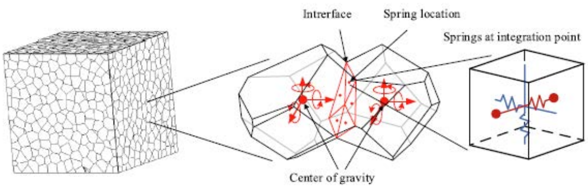

Fig. 3 RBSM Model

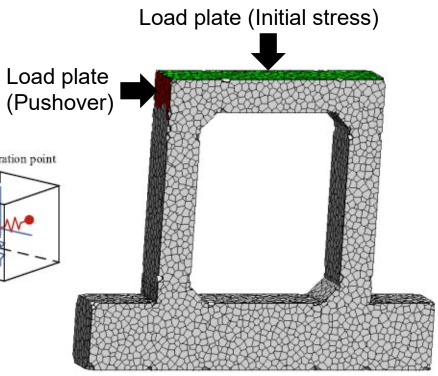

Fig. 4 Meshing of Test

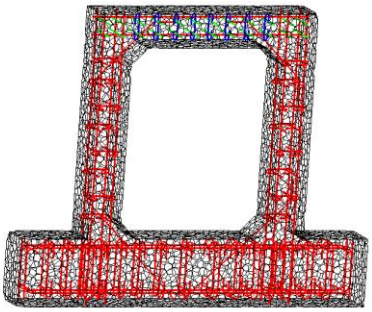

Fig. 5 Rebar arrangement in Model

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3. Comparison of Numerical and Experiments Results

Fig. 6 shows preliminary load-displacement relationship (P-Δ) comparison of test (dynamic) and numerical evaluation (static) of the box culvert. In test, load was calculated by multiplying top horizontal acceleration to the summation of imposed top weight (2.093t) and weight of top slab (0.331t). During the test, when acceleration reached to 4000gal, the longitudinal rebar yielded and the natural frequency of the specimen decreased, making it impossible to input acceleration further, so the first excitation was terminated. Overall, flexural failure proceeded as designed. In comparison to test, numerical model simulated similar pre-peak stiffness, peak flexural load, and displacement at peak flexural load. Overall numerical model could simulate well the load-displacement envelop in comparison to the test.

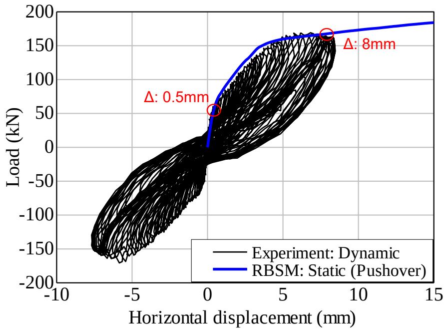


Fig. 6 Load-displacement

Fig. 7 expresses final stage cracking observed in test. A number of horizontal cracks occurred in vicinity of hunches, confirming the occurrence of bending failure mode. In numerical evaluation too, formation of a number of flexural cracks in vicinity of hunches is clearly found (Fig. 8.a: Δ: 8mm) that shows a good co-relation to the test. Furthermore, Figs. 8.b and 8.c show numerically observed vertical normal stress distribution (σ_y) in pre-crack stage (Δ: 0.5mm) and post-yield stage (Δ: 8mm) respectively. At 0.5mm displacement, localization of concrete tensile stress at the hunches area is obvious, whereas, middle portions of walls do not show any signigicant stresses. This clearly identifies that the surrondings of hunces are prone to the cracking. As, in post-yield stage (Δ: 8mm), dominant formation of flexural cracks in vicinity of hunches accompained by significant reduction in concrete tensile stresses is clearly observed. Infact, it also outlines that the section of longitudinal rebar in hunches area underwent yielding, and are prone to the rupture under dynamic loading as observed in the test.

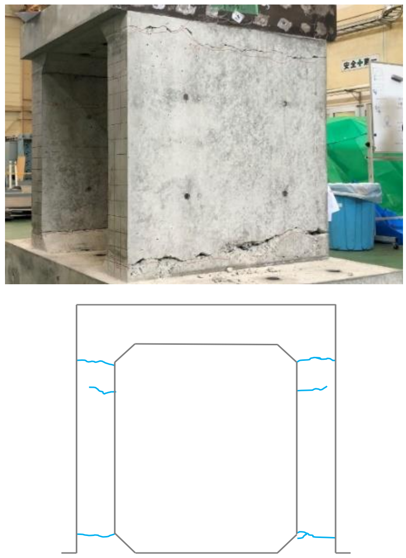
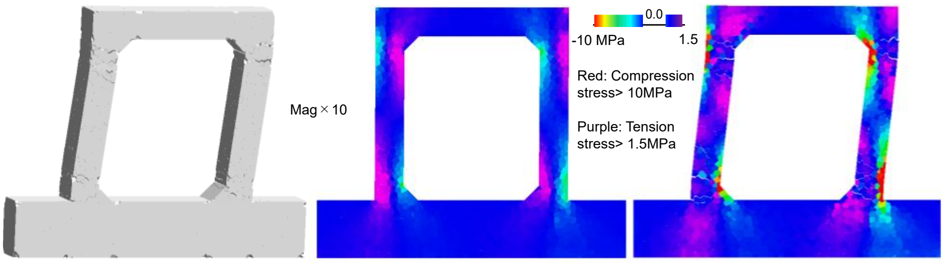


Fig. 7 Cracks in Test (Final Stage)

4. Conclusion

A preliminary comparison between high-acceleration seismic test on box culvert and numerical evaluation using 3D-RBSM showed that numerical model is capable to reproduce load-displacement behavior (static loading) compared to experiments (seismic loading). Most importantly, numerical model can simulate the damage induced due to the bending deformation such as cracks near the haunches of box culverts as well the stress distribution mechanism under crack propagation. In the future, we plan to use 3D-RBSM for the dynamic evaluation of coupled system of structure and equipment in order to advance in the fragility evaluation method. Also, detailed damage assessment will be performed for the coupled system including the anchors by using the inherent capabilities of 3D-RBSM to simulate the internal cracking and stress distribution.



(a) Deformation (Δ: 8mm) (b) σ_y (Δ: 0.5mm) (c) σ_y (Δ: 8mm)

Fig. 8 Deformation and Stress Distribution (σ_y) in Numerical Model

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1) Japan Society of Civil Engineers Nuclear Civil Engineering Committee: Guideline and Manual for Verification of Seismic Performance of Important Outdoor Civil Engineering Structures at Nuclear Power Plants, 2021.

2) Yamamoto, Y., Nakamura, H., Ichiro, K., Nonukai, F.: Crack Propagation Analysis of Reinforced Concrete Wall under Cyclic Loading using RBSM" European Journal of Environmental and Civil Engineering, 2014