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Division III

Dynamic Simulation of Nuclear Power Plants Subjected to Secondary Fault Displacement by Dynamic Rupture Simulation and Domain Reduction Method

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ABSTRACT

In the evaluation of the impact of fault displacement on structures, there are issues such as the superposition of earthquake motion and fault displacement, dynamic effect assessment, and so on. It is effective to use dynamic rupture simulation to simulate fault activity and structures as a whole. On the other hand, modeling a detailed structure, surrounding soil and a wide fault at the same time makes model scale and post-processing complicated, and it is difficult to perform parametric studies with multiple cases. Therefore, this study focuses on the domain reduction method and applies DRM to simulate dynamic rupture and evaluate the response of important structures near the ground surface. We compared the results of the main and secondary faults modeled as a whole with the results using the domain reduction method and showed that the two methods give comparable results. In addition, a model with a culvert directly above the sub-fault was created, and the effect of sub-fault displacement caused by the main fault activity on the culvert was evaluated.

INTRODUCTION

In recent years, the importance of the effects of not only earthquake motion but also fault displacement on structures has been widely discussed to ensure the safety of critical structures, especially nuclear power plants. Regulations for nuclear power plants in Japan prohibit the construction of critical structures such as nuclear power plants not only at sites with existing earthquake faults but also at sites where fault displacement is likely in the future. On the other hand, it is necessary to conduct a quantitative evaluation of the safety of structures when subjected to fault displacement from the perspective of design-basis external events and probabilistic risk assessment. In addition, a situation where a sub-fault that has no geometrical connection with the main fault becomes active due to the activity of the main fault can be assumed. In such cases, the superposition of earthquake ground motions with wide-area ground deformation caused by the sliding of the main fault is another problem to be considered.

Various methods have been proposed and implemented to simulate the behavior of structures subjected to fault activity. Fault rupture phenomena and their effects on critical structures are summarized in a report by the On-site Fault Assessment Method Review Committee (2014). In that report, as shown in Figure 1, a two-step analysis of structures subjected to fault displacement is presented. The reason for this is that it is difficult to evaluate both the fault and the structure at once due to the difference in their sizes.

The proposed two-step analysis simplifies the problem and uses a static approach to evaluate the problem. First, the displacement response of the ground over a wide area caused by the rupture of the main fault is calculated using the elasticity of discrepancy theory. Then, the calculated displacements are statically applied to the boundaries of a model consisting of a region composed of a relatively detailed model of the structure. However, the report also points out the need for further research to better understand the dynamic effects of both fault displacement and earthquake motion on structures to ensure the safety of existing nuclear power plants. In particular, the issue of superposition of fault displacement and seismic motion cannot be studied using this approach.

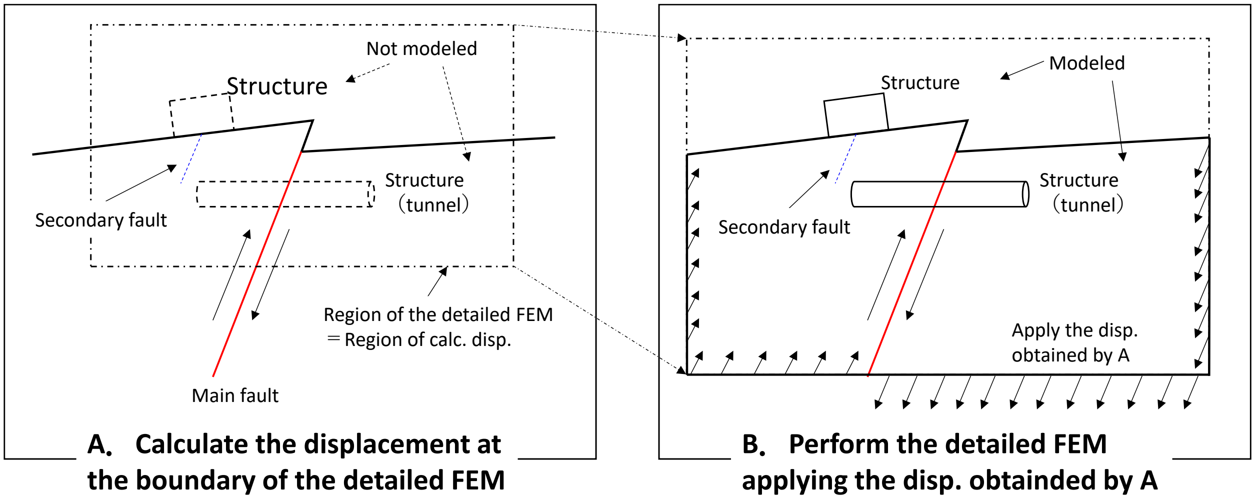


Figure 1. Investigation of the influence of fault displacement by a two-step analysis

The study by Rajasekharan et al. (2019) reported differences in the behavior of tunnels subjected to fault displacement simulated using static and dynamic approaches. They quantitatively evaluate the dynamic effects of fault slip, as well as the high computational cost and difficulty of parameter studies.

Dynamic rupture simulation using the finite element method has an advantage over other analytical methods in that it can consider the spontaneous rupture of faults in the dynamic study. However, since fault rupture simulation requires modeling of the entire fault over a wide area, the scale of the analytical model becomes too large to evaluate the behavior of structures and other objects near the ground surface with the desired accuracy, making it impractical to use in practice.

In this study, a customized FrontISTR (FrontISTR Commons) is used to evaluate the behavior of ground subjected to simultaneous earthquake ground motion and fault displacement. The two-step Domain Reduction Method (DRM) of Bielak et al. (2003) is used to separate the model of the wide-area consisting of the entire fault from the near-surface model, thereby reducing the computation time. A dynamic rupture simulation modeling the main fault is used as the first stage of analysis, and the external forces obtained from the results using the domain reduction method are input to the second stage model.

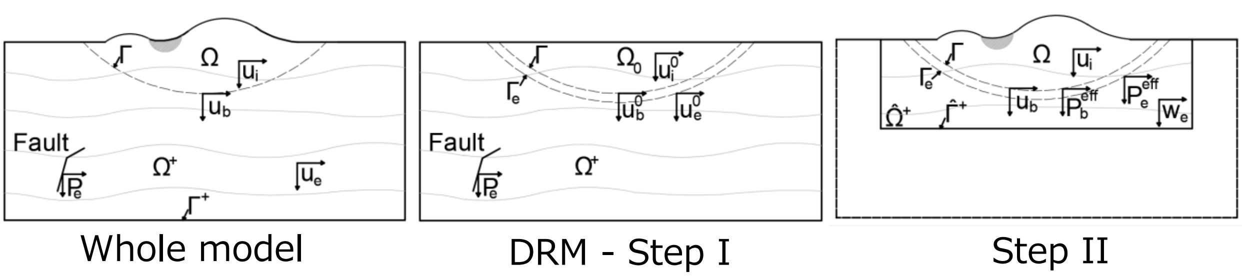


Figure 2. Image of the analysis area partitioning in DRM

VERIFICATION ANALYSIS MODEL

Mitsuhashi et al. [5] have previously conducted a 3-D dynamic rupture simulation of the Kamishiro fault earthquake, and the parameters of the 2-D analytical model were determined based on the conditions that were back-calculated to fit the analytical results to the observation record. The ground is a solid element, the fault is a joint element, and a viscous boundary modeling radiation damping is assigned around the ground. The earthquake on the Kamishiro fault is reported to be a reverse fault with lateral displacement, and the 3D FEM study by Mitsuhashi et al. was modeled according to that report. In this study, however, the fault was modeled as a pure reverse fault for the convenience of modeling in two dimensions. The analytical model used in this study is shown in Figure 3.

By employing DRM, the original problem of modeling fault displacement and seismic motion (the whole model) is replaced by STEP1 (the wide-area simple model) to simulate the dynamic rupture of the main fault, and STEP2 (the partial model) to perform dynamic analysis with a reduced target area so that local geology and induced sub-fault rupture can be considered. As STEP1, the response displacement and velocity-time histories of each node are calculated by examining only the main fault without modeling the sub-faults. From the obtained response time histories, equivalent excitation forces are calculated by the DRM and input into the partial model in STEP2. In the partial model, sub-faults are modeled as shown in Figure 3. For validation, an analysis of the overall model, in which the main and secondary faults are modeled simultaneously, is performed and the results are compared.

The main fault is modeled with joint elements that consider the nonlinear slip-shear stress relationship of the fault as shown in Figure 4, and viscous boundaries are set at the bottom and sides of the model. In the dynamic rupture simulation, a value exceeding the strength is given as the initial stress at the rupture initiation point, and the element at the rupture initiation point fails as soon as the analysis starts. Spontaneous rupture of the fault occurs as stress is released and redistributed to the surrounding area. The mesh size is approximately 100 m, excluding the peripheral area of the sub-fault. In addition, a sub-fault with the same orientation and 45-degree dip as the main fault was modeled at about 6.5 km from the lower plate side of the sub-fault. The model is based on the expectation that displacement will be induced in the sub-fault due to earthquake ground motions generated by the rupture of the main fault and ground deformation in a wide area. The sub faults were modeled by joint elements following the nonlinear constitutive law of bilinear. The stiffness of the sub-fault is 0.02 m in thickness, and the physical properties are the values in Figure 4 as depth-dependent strength with reference to the Nuclear Civil Engineering Committee. (2009). Depth-dependent strengths were determined by interpolating and extrapolating the discretely indicated strengths for the constraint pressure.

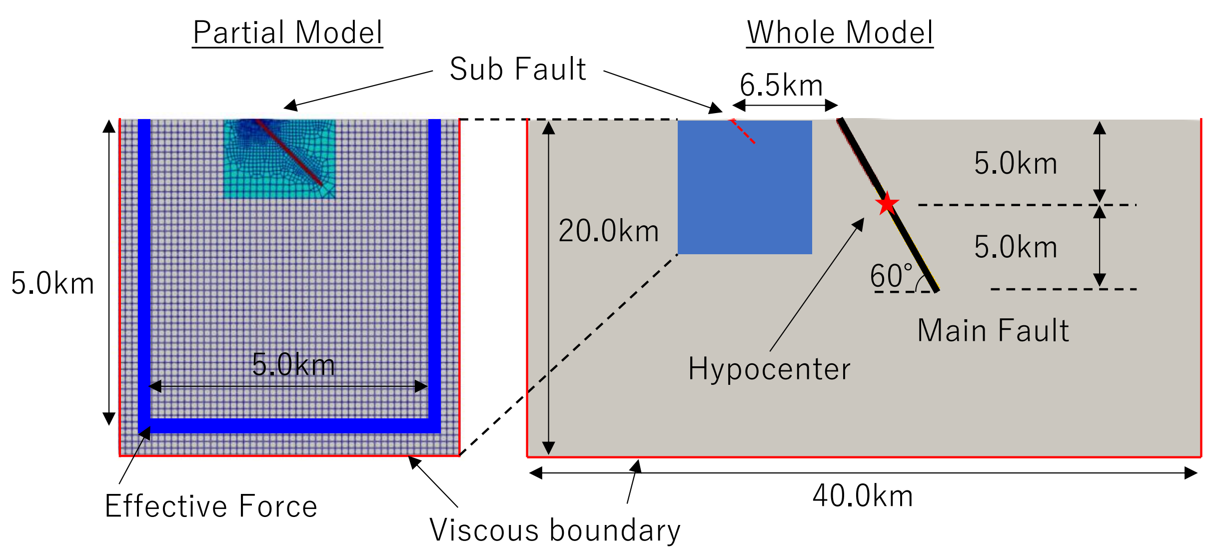
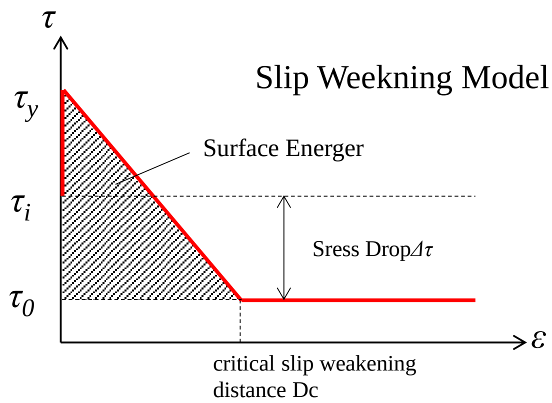


Figure 3. Image of the validation analysis



Main Fault Parameters		
Width	(km)	11.5
Length	(km)	-
Slope	(Degree)	60
Stress Drop	(MPa)	2.66
Dc	(m)	0.15
Sub-Fault Parameters		
Youngs Mod.	(kN/m^2)	1.76E+05
Thickness	(m)	0.02
Strength	(kN/m^2)	8.14Z+158 (Z: depth(m))
Rock Parameters		
Youngs Mod.	(kN/m^2)	8.620E+07
Poisson Ratio	(-)	0.25

Figure 4. Nonlinear constitutive law of faults and property values

VERIFICATION ANALYSIS RESULTS

The displacement time histories of the sub-faults for the STEP2 model with DRM and the whole model are shown in Figure 5. The acceleration time histories at the nodes on the lower plate side of STEP2 are also shown. The displacement time histories of the whole model and DRM results generally agree with each other, indicating that DRM can be applied to some extent in the studies targeted by this study. Factors contributing to the difference between the two include the modeling of semi-infinite ground with a viscous boundary. Comparing the acceleration time history with the displacement time history, the acceleration occurs first, although the absolute level of acceleration is small, and then the displacement of the sub-fault begins to occur. This may be because the propagation of displacement is small compared to the propagation velocity of seismic motion in general earthquakes. In the present study, it is assumed that the acceleration-induced displacement of the fracture zone is small and that the displacement of the fracture zone is dominated by the ground deformation over a wide area because of the small acceleration.

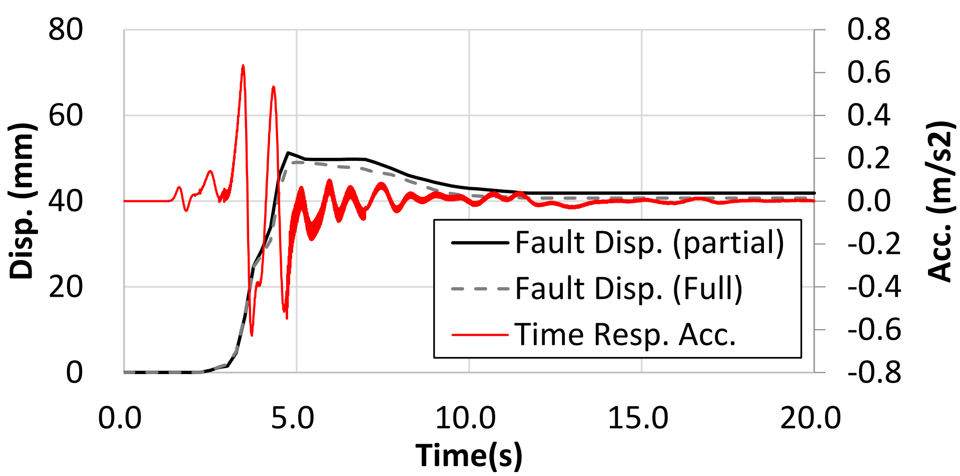


Figure 5. Response displacement and acceleration time history

The displacement-stress relationships at several locations on the sub-faults are shown in Figure 6. The stress-strain relationship is plotted every 0.25 s for output convenience. In the near-surface area, the sub-fault elements fail at a relatively early stage, indicating that the stiffness of the sub-fault elements decreases and then strain develops significantly. After the element fails under positive stress and slipping develops, the direction of slip turns in the opposite direction, stiffness is restored, and the element fails in a negative direction. However, it is unclear how actual fracture zones behave when subjected to reverse displacement after a fracture. In this study, bilinear nonlinear properties were used, but the trend may change if nonlinear properties closer to reality are used.

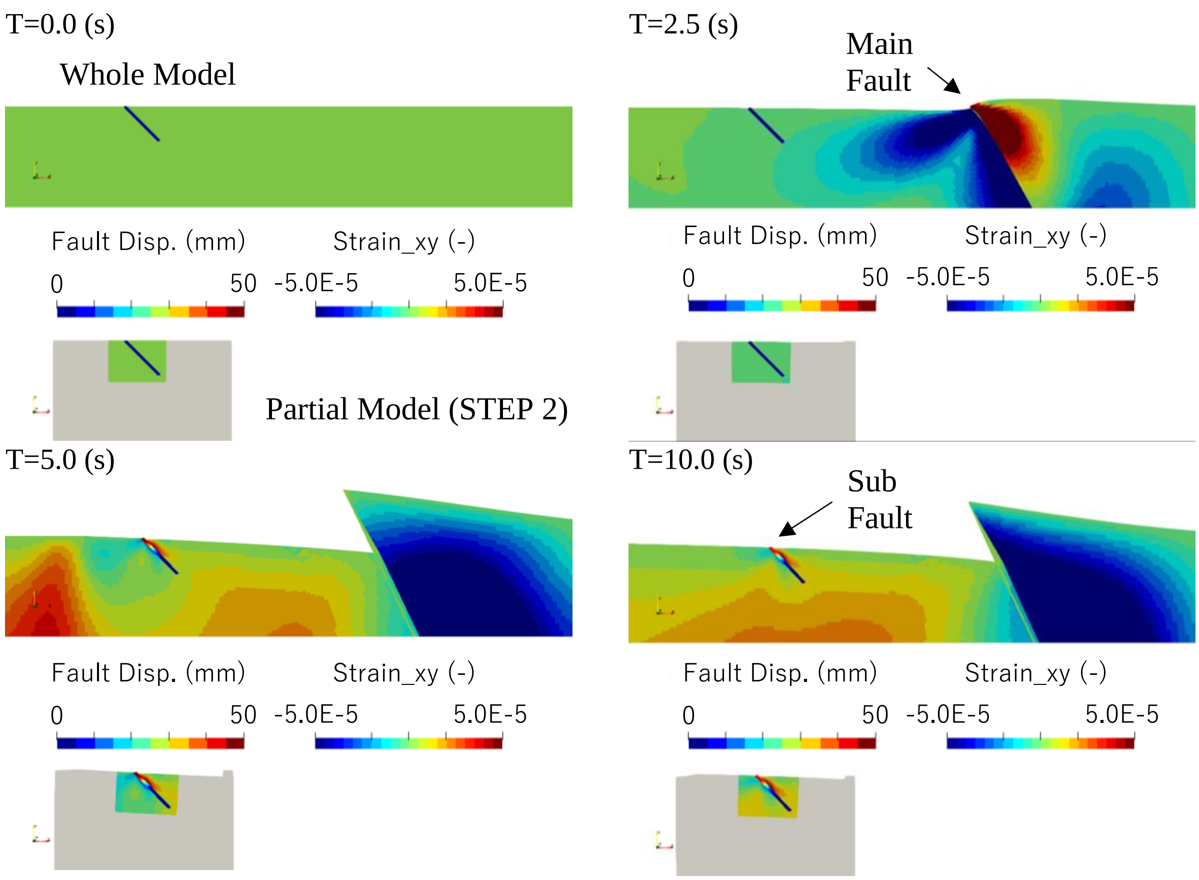


Figure 6. Comparison of analysis results between the overall model and DRM (deformation diagram (50x deformation) and shear strain contour diagram)

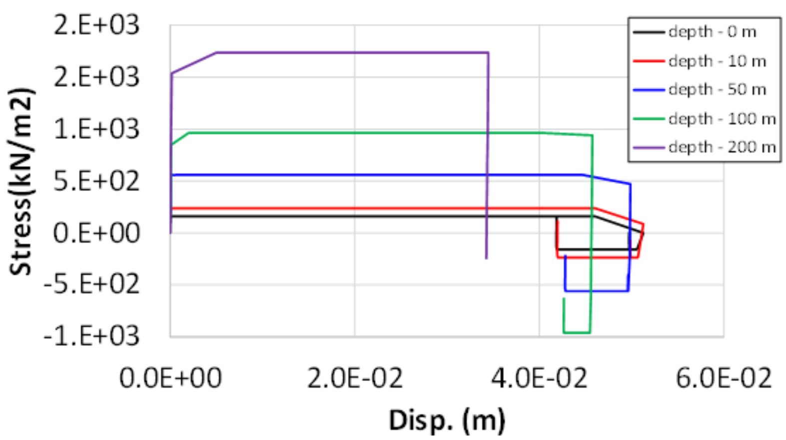


Figure 7. Stress-displacement relationship of sub-faults

STUDY OF EFFECTS ON RC CULVERTS

For the analytical model studied in the previous chapters, a culvert was modeled directly above the sub-fault in the analytical model of STEP 2 using linear solid elements, and the analytical model was set up so that the culvert was subjected to the displacement of the sub-fault as shown in Figure 8. The culvert is 10 m wide and 5 m high, with a wall thickness of 1.0 m. The model for the shape of the culvert, etc., was created with reference to the Nuclear Civil Engineering Committee. (2018). It is embedded in a 7.5 m thick layer of surface soil. The surface soil was linear and wide enough to span 500m. The stiffness of the added sections in this model is shown in Table 1. Joint elements were set up between the culvert and the surrounding ground/rock to account for separation. The joint elements have stiffness in compression-only and do not transmit forces in separation or shear. The physical properties of the culvert and surrounding soil are shown in Table 1.

The deformation diagram (deformation: x10) and tensile(upper)/compressive(lower) principal stress contour diagram of the culvert at the time of maximum displacement and at the final time of the analysis (20 seconds) are shown in Figure 9. The culvert is deformed to the point of overturning as a whole due to separation from the ground/soil at the sidewalls and bottom. A comparison of the contour diagram at the time of maximum sub-fault displacement and at the final time of the analysis shows no significant difference. Tensile stresses in the culvert are higher just above the sub-faults and above the upper part of the top plate, exceeding the tensile strength of concrete by about 2000 kN/m^2. Considering that the amount of displacement directly under the structure is about 40 to 50 mm, the stress generated in the concrete itself is not so big due to overturning, but the cracking strength of the concrete is exceeded. In the future, we would like to conduct studies that take into account the nonlinearity of concrete to evaluate its behavior more precisely.

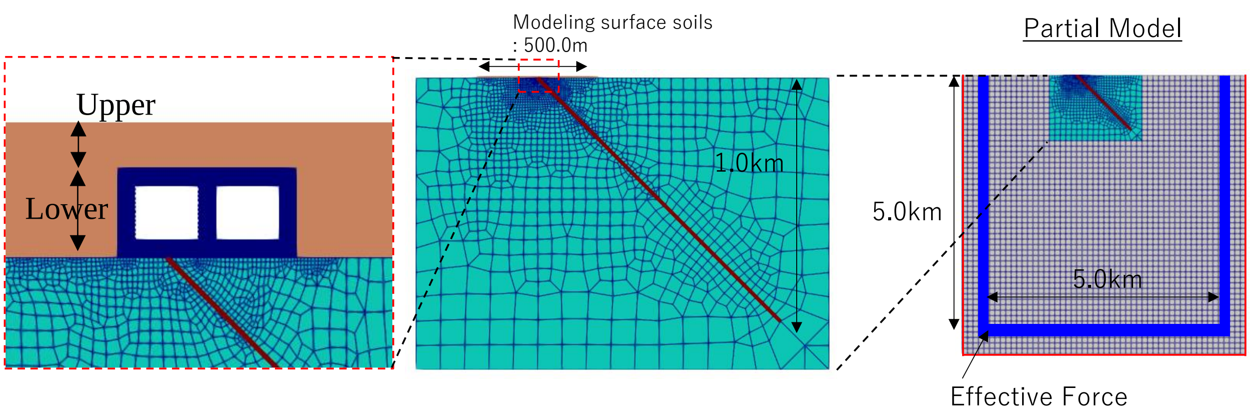


Figure 8. Analytical model for effect study on culverts

Table 1. Analytical Properties in Culvert Studies

	Young's mod.	Poisson ratio	Unit Weight	Strength
	kN/m^2	-	kN/m^3	kN/m^2
Upper Soil	1.00E+04	0.25	20	Linear
Lower Soil	5.00E+04	0.25	20	Linear
Concrete	2.00E+07	0.20	24	Linear

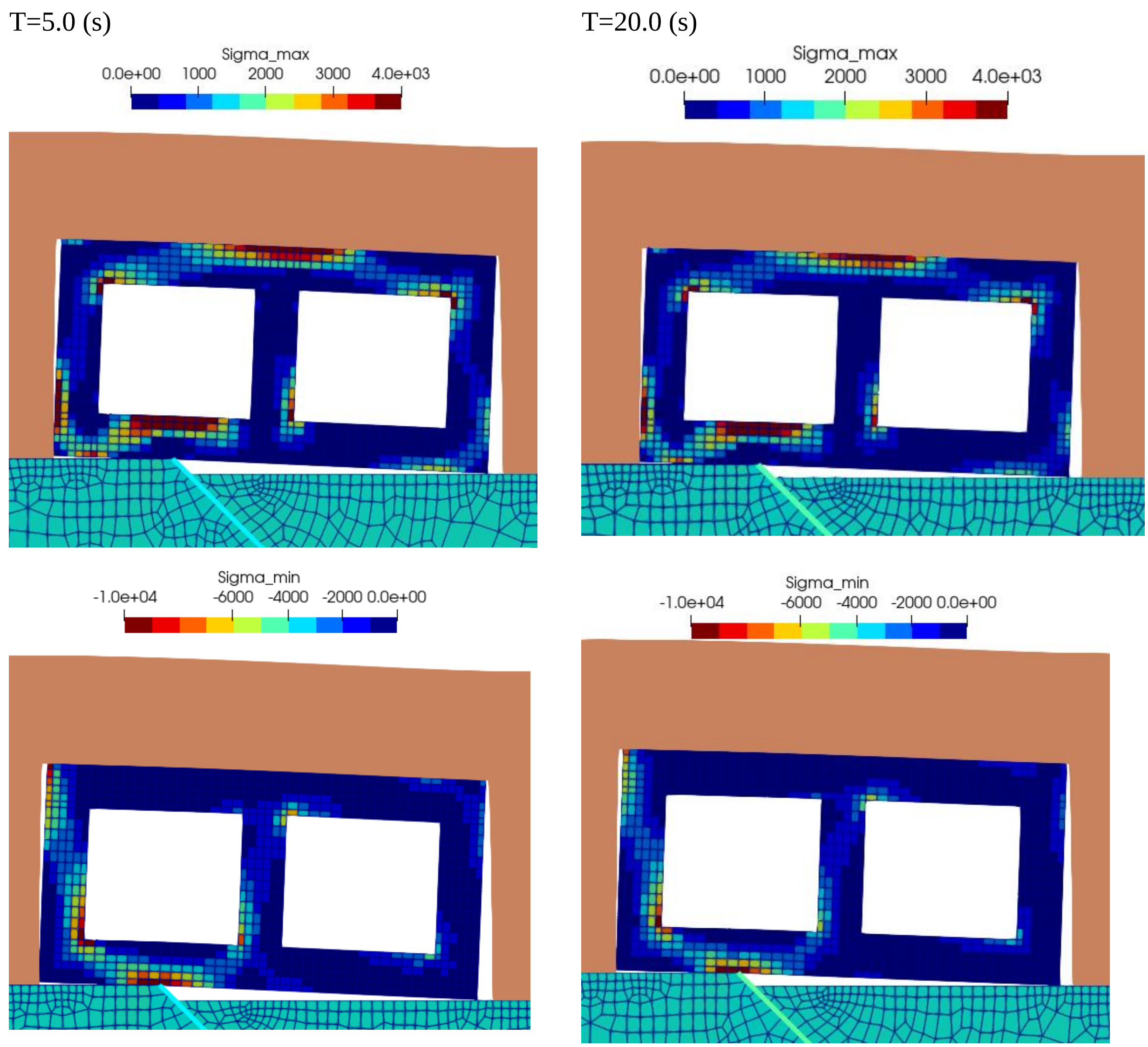


Figure 9. Culvert deformation diagram (10x deformation)
and tensile(upper)/compressive(lower) principal stress contour diagram (Unit: kN/m^2)

CONCLUSION

In this study, we evaluated the behavior of RC culverts installed directly above sub-faults when subjected to fault displacement. The entire main fault was modeled by dynamic rupture simulation, and the associated displacement of the sub-fault and the behavior of the culvert were examined by DRM. First, we compared the results of DRM with those of a model that models the main and sub-faults as a single unit. It was shown that the problem can be represented to some extent by DRM.

Next, a culvert and surface ground were modeled directly above the sub-fault using the DRM STEP2 model. The response of the culvert to overturning was obtained, indicating that the response of the culvert can be quantitatively evaluated. In the future, we would like to conduct more detailed evaluations that take into account the sub-fault conditions and the nonlinearity of the culvert and the surface soil.

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