論文の内容の要旨

論文題目　Failure mechanism of concrete structures under fault-induced ground surface rupture and deformation by Voronoi Applied Element Method

（断層運動が引き起こす地表変状によって生じるコンクリート構造物の破壊メカニズムのボロノイ分割応用要素法解析）

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In 1999 Chi-Chi Taiwan and 1999 Kocaeli Turkey earthquake, many structures failed due to the surface rupture caused by fault movement. The damaged structures including dam, bridges and buildings were failed by ripping apart, shearing and shifting from their foundation. The failure due to surface rupture has been occurred many times in the past earthquake however there is still no standard for protecting those structures. At present, the best way to mitigate this hazard is to avoid building new structures in the faulting area. In order to prevent the damage, the failure mechanism of the existing structures under the fault action must be understood therefore the rehabilitation plan can be carried out.

The structures damaged by the fault movement are both sitting directly on the bedrock or embedded in the soil. In the case that the structures are placed on the bedrock, the modeling of the fault movement can be considered as the rigid movement at the structural foundation due to very high bedrock's stiffness. On the contrary, in the case that structures are embedded in or place on the soil, the soil's stiffness becomes more important because of its relatively low stiffness compared to the structure. Therefore, the deformation generated by bedrock will also be absorbed by the soil. Unless the soil surrounding the foundation is modeled, the structural behavior cannot be accurately obtained. Therefore, in this case, it is also important that the model must be used to simulate both structure and soil, simultaneously.

Studies of the failure mechanism can be achieved by using two approaches: experimental and numerical approaches. Although, experimental method is more realistic because it can include all the complex behaviors, it is usually uneconomic and time consumed. In contrary, the numerical approach is considered to be more economic and less time consumed. Moreover, the numerical model has been fast developed and the more recent model usually exhibits the better result. The other advantage of the numerical approach is that the model has no need to be scaled in both physical and time domain and it is possible to run the problem many times with no more expense.In this study, the Applied Element Method (AEM) was selected as a numerical tool because its ability to follow the behavior from the elastic to very large deformation. The improved version of AEM called Voronoi Applied Element Method (VAEM) has been developed to improve the capacity of the previous AEM version. VAEM contains Voronoi shape element rather than using only one size square element as in original AEM. The advantages of VAEM are that 1) it is easier fit to any physical domain 2) it is able to have a predefined joint face within the domain in any direction, 3) it contains implicit Poisson's ratio (ν), 4) it allows user to use different element's size and 5) it reduces the crack directional biased.

The ability of VAEM to follow the behavior of plain and reinforced concrete was verified. In all cases, the obtained crack locations agree well with the experimental results. In case of RC simulation, the crack patterns obtained from VAEM was found to be more accurate than original AEM. Because VAEM can develop the diagonal crack closer than AEM, VAEM exhibits less maximum resistant compared to the original AEM.The analysis of soil deposit under the fault action was carried out by VAEM. The analysis results were compared to the original AEM. It was found that the influence length on the ground surface rupture tends to reduce in soil deposit with weaker strength. Moreover, crack propagations and direction from VAEM are similar to original AEM however VAEM shows the clearer shear band characteristic. Finally, Elastic results obtained from VAEM are in good agreement with original AEM.

The static non-linear analysis of Shih-Kang dam was carried out. Parametric studies including dip angle of the fault, fault location, ground deformation shape and dam height were studied. it was found that Shih-Kang dam damage mechanism starts from the separation of the dam from its foundation, cracks from the top of the dam, shear cracks and compression failure. The analysis result indicated that Concrete dam like the case of Shih-Kang dam can resist very low amount of fault induced ground rupture and deformation. From parametric studies, it was found that under the normal fault, the dam would be damaged at the lower displacement than the reverse fault. Moreover, location of the fault also has an effect on the maximum resisting displacement. With the different ground deformation, the one that creates the maximum curvature will damage the dam at the lowest displacement. Therefore, the discontinuous deformation like the fault rupture can damage the dam at the lowest amount of displacement. Under the same fault rupture, the dam height does not have significant effect on the level of maximum resisting deformation. Based on the understanding of damage behavior, the rehabilitation of Shih-Kang dam was proposed by placing the slip joint and additional concrete back fill under the dam.

In the analysis of bridge under the fault action, the case of Arifiye overpass was selected. It was found that the connection of the bridge girders could cause the progressive collapse of the other girders far from the fault. The analysis of reinforced concrete building indicates that the difference in dip angle can result in different modes of building failure. In case of 90^o normal and reverse fault, the failure is focused in the beam near the fault however in case of 45^o and 90^o dip angle, the damage in the columns was also found. Moreover, it was also found that the building tends to resist higher displacement in case of reverse fault. The simulation of reinforced concrete pipe shows that, 90^o in case of 90^o dip angle, the damage of the concrete pipe is consisted of shear and tension failure. The shear failure occurs in the footing wall while tensile failure occurs in the hanging wall.