

HIGH PERFORMANCE COMPUTATION AND WALKTHROUGH VISUALIZATION FOR ASSESSING SEISMIC SAFETY OF NUCLEAR POWER PLANTS

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ABSTRACT

We have been developing a multi-scale and multi-physics based numerical simulator for quantitatively predicting actual quake-proof capability of ageing NPPs under operation or just after plant trip subjected to strong earthquake. Here we divide the whole phenomena into three sub-phenomena, and develop simulation codes and numerical models for the sub-phenomena. As for a main sub-phenomenon, we construct full scale and precise 3D finite element models of building, pressure vessels with internal structures with nearly billion degrees of freedom, and perform dynamic nonlinear response analyses with considering fluid-structure interaction between pressure vessel, internal structures and coolant by iterative partitioned coupling algorithms. We also develop a parallelized walkthrough visualization technique to effectively deal with a huge amount of data coming from large scale dynamic simulations. Those simulation codes are now being tuned for Japanese Peta-flops computer “K” with sub-millions cores. In this paper, we describe key algorithms of the simulation methods and some preliminary results.

INTRODUCTION

In such countries as Japan where earthquake occurs frequently, reliable and sufficient seismic proof design plays a key role in operating nuclear power plants (NPPs) safely and stably. Especially, recent strong earthquakes attacking some Japanese NPP facilities such as Niigataken-Chuetsu-Oki (NCO) earthquake with 6.8 Mw occurred on July 16, 2007 and Off the Pacific Coast of Tohoku Earthquake / Tsunami with 9.0 Mw occurred on March 11, 2011 recalled its practical importance seriously. In the NCO earthquake, the JMA intensity of nearly 7 was observed in the site of the Kashiwazaki-Kariwa NPPs of The Tokyo Electric Power Company (TEPCO), and the seismic wave detected on the base mat of the unit 1 reactor building was 680 gal in the east-west direction. During the earthquake event, Units 3, 4 and 7 were in full-power operation. The maximum value of the observed response acceleration exceeded a design limit, and the observed response spectrum exceeded the design spectrum in a whole frequency range. Although safety-related components were not damaged at all, various damages were observed in non-safety related structures, systems and components (SSCs). As the results, the plants have been stopped over two years.

When Off the Pacific Coast of Tohoku Earthquake / Tsunami occurred, 11 units among 14 units of 4 NPP facilities located along the east coast of Tohoku area were under operation. The 11 units were safely shutdown with automatic scram systems. Among 6 units of TEPCO's Fukushima Dai-ichi NPP Facilities, Nos.1-4 units failed in containing radioactive materials inside due to long term loss of all cooling capabilities due to a series of Tsunami waves of huge height far exceeding a design limit. Actual causes of the nuclear accidents and actual damaging processes of the NPPs' SSCs due to either or both seismic loading and Tsunami waves will need to be precisely investigated after the accidents are settled down. On the other hand, considering the facts that 54 units currently exist in Japan, it is urgent and crucial to accurately evaluate seismic proof capabilities of each NPP subjected to strong earthquake far exceeding its design limit, and to take appropriate actions a priori to prevent nuclear accidents.

In conventional seismic design of NPPs, a variety of safety margins are embedded in various ways in order to consider uncertainty in design and operation processes such as a magnitude of earthquake, material strength and operating conditions. It had been recognized till the accidents of March 11, 2011 that because of such a variety of safety margins, safety-related SSCs were not damaged even though they were subjected to stronger seismic loading than the design limit. However, it is still unknown how strong earthquake the existing NPPs can stand in reality. In other words, the following question is now raised, i.e. how much safety margin does NPP have in reality against strong earthquake ?

If possible, it would be preferable to ensure quake-proof capability of socially-important artifacts such as NPPs subjected to strong earthquake by real-scaled mockup experiments. However, it is impossible to shake a real NPP even using a world-largest shaking table, E-Defense [1] constructed in April 2005 due to its limitation in load

and acceleration capacity. Furthermore, it should be noted that the actual shaking table approach can not examine seismic response of NPP under operation.

Under the above-mentioned background, since September 2007, we have been developing a multi-scale and multi-physics based numerical simulator for quantitatively predicting actual quake-proof capability of ageing NPPs under operation or just after plant trip subjected to strong earthquake [2]. In this paper, we describe an overview of the simulator with some preliminary results.

MULTI-SCALE AND MULTI-PHYSICS SIMULATION

Research Strategy

In the present research, we define the performance limit of NPP under operation or just after plant trip subjected to strong earthquake as “Quake-proof Capability”. We are now developing a numerical simulation system to quantitatively evaluate the quake-proof capability of NPP subjected to strong earthquake. To realize this, we employ a multi-scale and multi-physics simulation approach. Figure 1 shows the illustration of its total image.

The whole phenomena ranging from mm to 100km in space and from 1000Hz to 0.1Hz in frequency include long distant wave propagation in crust, coupled shaking motion of ground, plant building and nuclear components, thermal hydraulic circulation in fuel assembly and neutron-coupled thermal hydraulic oscillation. Time duration of an earthquake event is typically over tens of seconds. Thus we need to consider multi-scale feature and multi-physics one simultaneously. To deal with the interaction among different temporal and spatial scale phenomena accurately as well as efficiently, we decide to divide the whole phenomena into three sub-phenomena, and construct different simulation methods and models for the three sub-phenomena as described next.

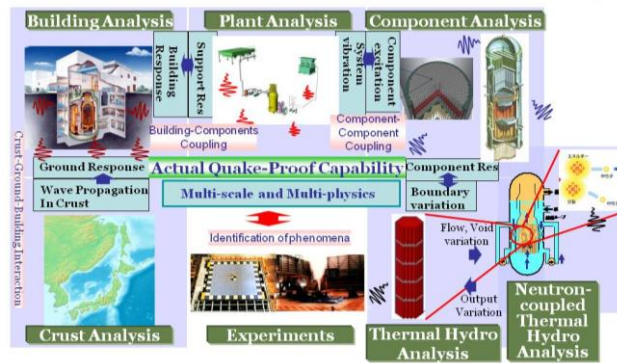


Fig.1: Total image of present simulator

Sub-phenomenon A : Long-distant Wave Propagation in Crust, Coupled Shaking of Ground and Building

As for a process of long-distant wave propagation in crust after an earthquake occurs over 10km far from NPP site, we calculate wave propagation phenomenon in crust using a precise model considering crust structure and coupled shaking of ground and plant building. Although this is linear calculation, it needs to calculate a very huge area ranging from meters to tens of kilometers. This becomes a huge scale of multi-scale analysis. In the vicinity of plant building, ground-building interaction affects wave propagation behavior. To take into account this effect, the dynamic response behavior of the building is first embedded in the global crust model, and the wave propagation is simulated precisely. Then the result is given to the precise model of the building surrounded by ground, and its nonlinear coupled-shaking process is simulated [3-5].

Sub-phenomenon B : Shaking of Building, Nuclear Components Considering Fluid-structure Interaction with Coolant

Current seismic design in Japan basically employs a lumped mass model, in which building and main components such as pressure vessel and internal structures are modeled as a collection of beam and mass elements. Since model parameters such as mass, spring constants and damping coefficients have been well tuned through past experiences of earthquakes and shaking table experiments of components, the model can well reproduce overall response of an actual NPP subjected to earthquake. A typical seismic analysis using the lumped mass model is as follows. At first, a dynamic response analysis is performed using the lumped mass model, and the maximum response of each component or each local portion is calculated. Providing the maximum response value to a precise

2D or 3D finite element model of each component or each local portion, a static deformation analysis is performed, and finally the maximum stress or displacement of each component or each local portion is calculated. In such a conventional seismic design process, a certain amount of safety margin is embedded in various processes. Therefore, the above simplified model works somehow well for design purpose. However, it is not sufficient to quantitatively evaluate an actual quake-proof capability of NPPs subjected to strong earthquake exceeding design limit. Thus we try to simulate the shaking phenomena of NPP systems and components as precisely as possible. To do so, we construct full scale 3D finite element models of building, pressure vessels with internal structures with nearly billion degrees of freedom. In addition, fluid-structure interaction effects between pressure vessel, internal structures and coolant are also precisely simulated.

Some of the present authors have been developing a general-purpose and open-source parallel finite element analysis system named ADVENTURE [6-9] since 1997. In the present study, we are enhancing the analysis capabilities of the ADVENTURE system in various directions, i.e. nonlinear analyses such as dynamic and cyclic elasto-plasticity of steels and nonlinear deformation of reinforced concrete structures, multiple-point constraint (MPC) analysis for large scale and complex assembled structures, high-performance computing (HPC) capability towards Peta-flops computer with sub-millions of cores, and general-purpose fluid-structure interaction (FSI) analysis with partitioned coupling algorithms [10-12]. In addition, we are developing several support tools for pre and post processes, including parallelized visualization tools for time varying analysis with a huge scale model over tens of millions of DOFs [13, 14].

Sub-phenomenon C : Neutron-coupled Thermal Hydraulic Circulation, and Thermal Hydraulic Behavior within Fuel Assembly

NPPs in Japan are designed so as to trip when sensing a certain level of earthquake, say an acceleration level of one to a few tenth of design earthquake's value. For this purpose, control rods are suddenly inserted into small gaps of fuel assembly, and nuclear reaction is stopped before main shock arrives at NPP site. Even though nuclear reaction stops, temperature inside the reactor is still kept high and coolant is circulated rapidly during the earthquake event. If plant trip fails due to any unknown troubles, nuclear reaction could continue as well. If pump for coolant circulation is damaged, coolant circulation could become unstable. Especially, in the case of boiling water reactors (BWRs), earthquake shaking might cause fluctuation of coolant volume and that of core void ratio. Therefore it is very important to assure whether stability of reactor core is maintained.

Relationship of Sub-phenomena A, B and C

The relationship among the three sub-phenomena A, B and C is modeled as follows. When simulating sub-phenomenon A, the coupling effect of building and ground on wave propagation in crust is already considered as described previously. When simulating sub-phenomenon B, the interaction of structural components, i.e. vessel with internal structures, and coolant is also considered. The result, i.e. a spatial distribution and time history of acceleration calculated from sub-phenomenon A is given as input to the simulation of sub-phenomenon B. The result of acceleration calculated from sub-phenomenon B is then given to the simulation of sub-phenomenon C.

SIMULATION MODELS AND PRELIMINARY RESULTS

Long-distant Wave Propagation in Crust, Coupled Shaking of Ground and Building

The crust-building modeling and the crust-ground-building modeling are in the following. In the crust-building modeling, the three kinds of 3D finite element models are constructed. The first model is used for the macroscopic analysis, in which crust-scale earthquake wave propagation is calculated as shown in Figure 2. The second model is used for the microscopic analysis, in which ground-scale earthquake wave propagation is calculated as shown in Figure 3. The third model is used for the soil-structure interaction computation of a nuclear power plant building as shown in Figure 4. The third computation is the nonlinear finite element analysis of reinforced concrete structure. Nonlinear constitutive relations of concrete, which account for both plastic deformation and damage accumulation, are taken into account here [3].

The crust-ground-building analysis consists of the following three phases: 1) a macroscopic analysis [4] in which the crust scale process of earthquake wave propagation is computed, 2) the microscopic analysis in the ground scale process of earthquake wave amplification is computed [4, 5], and 3) the soil-structure interaction analysis which computes possible failure of NPP buildings.

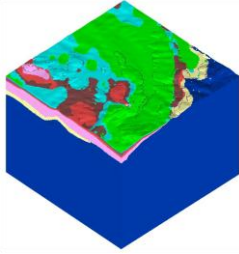


Fig. 2: Finite element model of crust

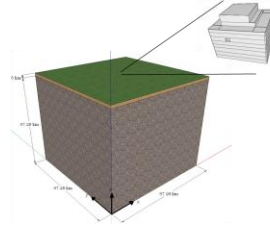


Fig. 3: Finite element model of ground and building

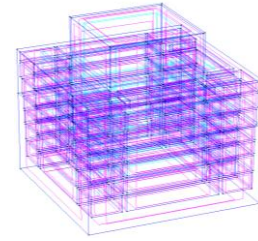


Fig. 4: Finite element model of NPP building

Shaking of Building, Nuclear Components Considering Fluid-structure Interaction with Coolant

Kinematic and mixed hardening law for cyclic plasticity, as ageing material models for reactor components, is implemented into the parallel structural analysis code, ADVENTURE_Solid. Several improvements, such as generalized input format for various types of strain hardening laws, and automatic control of increment during transition from elastic to plastic state and unloading, have been incorporated as well.

A feature of multiple-point constraint (MPC) analysis is implemented into ADVENTURE_Solid, assuring excellent convergence of DDM-based iterative solutions. A new GUI-based tool for attaching MPC boundary conditions, named ADVENTURE_BCtool+ is also developed.

A coupling tool for large scale parallel coupling analyses among seismic ground motion, shaking of plant building, dynamic response of reactor structural components and coolant, named ADVENTURE_Coupler, is newly developed [12]. The coupler consists of three components, i.e. communication library for parallel solvers, coupling agent programs to perform mapping processes such as actual geometrical interpolation and send-receive of boundary values, and a program to generate a mapping relationship between parallel solvers. All the data on fluid-structure interface boundary are sent and received through the mapping processes. The communication library is used for handling parallel communication among solver processes and mapping processes. The library is directly linked into solvers. The standard TCP/IP socket is used for the communication between a solver process and a mapping process, while MPI is used for the communication among mapping processes within the coupler.

As a preliminary coupling analysis, FSI simulation is performed for vibration of extruded rod bundles immersed in fluid. Here to consider added mass effects on fluid-structural interaction in seismic response of NPP, a two-way coupling analysis with Poisson's equation-based acoustic fluid and structure is performed. As iterative coupling algorithms, the Broyden method is used [11]. Figure 5 shows a snapshot of calculated displacement and pressure distribution. Figure 6 shows the CAD model of nuclear pressure vessel with internal structures, and that of a portion of coolant.

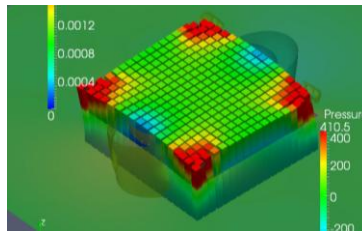


Fig. 5: Snapshot of FSI vibration of extruded rods immersed in fluid

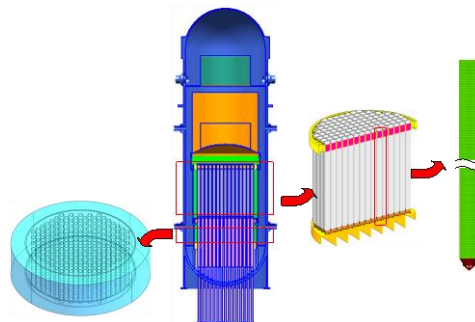


Fig. 6: Precise CAD models of vessel, internal structures and coolant

Neutron-coupled Thermal Hydraulic Circulation, and Thermal Hydraulic Behavior within Fuel Assembly

As for neutron-coupled thermal hydraulic calculation and core thermal hydraulic calculation, the modified coupled 3D neutron-kinetics and thermal-hydraulics code (TRAC-BF1/ SKETCH-INS) is employed with additionally implementing a seismic acceleration model into the motion equations of the code. Figure 7 depicts the results obtained from the analysis of a plant subjected to horizontal as well as vertical sinusoidal acceleration waves. Core power response curve shows reasonable results such that the period of power oscillation is equal to that of the acceleration.

As for the thermal hydraulic analysis in fuel assembly, ACE-3D code is employed. In the analysis, to apply earthquake acceleration data and unsteady boundary condition data such as inlet velocity to thermal hydraulic analysis, a high-order interpolation method is introduced to ACE-3D code. In order to verify the improvements of the code, boiling flow in fuel assembly, where earthquake acceleration is imposed to fluid, is calculated as shown in Figure 8. The figure clearly shows that fluctuation of void fraction in the fuel assembly occurs with the same period of earthquake acceleration.

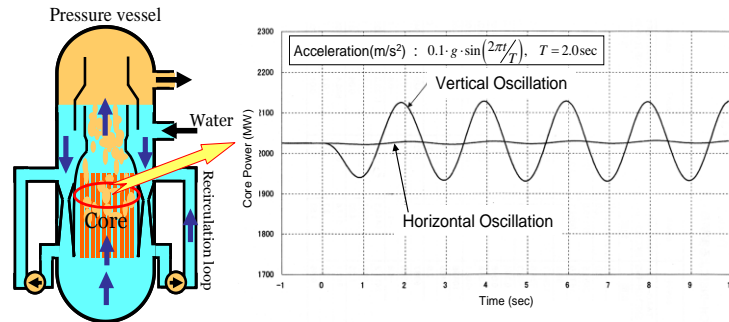


Fig. 7: Core power response to sinusoidal acceleration

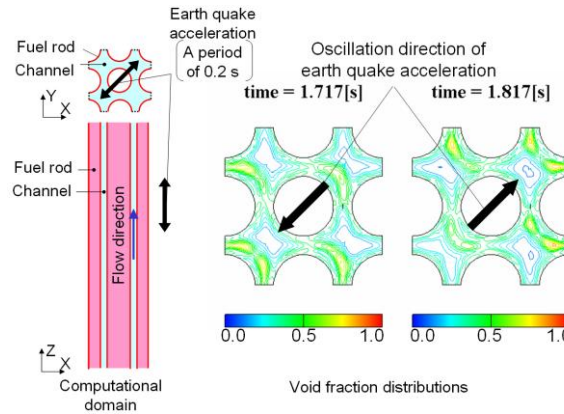


Fig. 8: Void fraction distribution obtained from boiling water flow analysis in fuel assembly

CONCLUDING REMARKS

We have been developing a multi-scale and multi-physics based numerical simulator for quantitatively predicting actual quake-proof capability of ageing NPPs under operation or just after plant trip subjected to strong earthquake. We divide the whole phenomena into three sub-phenomena, and develop simulation codes and numerical models for the sub-phenomena. In the next stage, those simulation codes and numerical models will be connected among others to solve the whole multi-scale and multi-physics phenomena. To do so, we need to utilize Peta-flops computers such as Japanese Peta-flops computer “K” with sub-millions cores [15]. The Great East Japan Earthquake and Tsunami on March 11, 2011 and its accompanied nuclear accidents made us recognize the importance such that seismic proof capability of not only RPV and piping, but also all other SSCs such as cooling facilities need to be proven. The present simulator will be useful for that purpose as well.

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