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TOPIC ②

MECHANICS

②.2 Structural Mechanics

②.2.2 Plant and seismic aspects

extended summary

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Overview and objectives

The purpose of this lecture is to provide: an outline of the nuclear safety requirements in the seismic range, the statement of basic dynamic phenomena governing the seismic behaviour of structures (main part of the lecture), a quick presentation of the engineering practice and recent R&D activities to improve methodologies and to put up with new safety requirements.

Introduction about seismic risk: stakes and requirements for NPPs

Nuclear Power Plant buildings role is to ensure the serviceability, protection of the environment and equipment involved in the whole process: nuclear vessel, associated circuits and components, other equipment. The main buildings constitutive of a NPP are: the containment vessel (protecting the major components), several nuclear auxiliary buildings (fuel, electric, pumping…), several non-nuclear buildings (cooling towers, turbine hall…); other civil works like embankments must not be forgotten. Main components (inner vessel structures, primary circuit…) and equipment are also to be justified against the seismic risk, found to be comparable with internally initiated events. All these structural elements need appropriate mechanical analyses, both at the design stage, in order to ensure safety, conservatisms, and life duration requirements, and during periodic safety re-evaluations, in accordance with the risk level. Four types of approaches are distinguished: the safety margin assessment, the "seismic event" one, the "risk informed" one, the "in depth defence" one. Deterministic and/or probabilistic methods are used; accordingly, several types of criteria ("seismic capacities") are defined: conventional limits of solicitations, maximal drifts…

Earthquake ground motion loading and probabilistic seismic hazard

The seismic hazard, established in terms of probabilistic data, is related to the seismotectonic evaluation of the site where the NPP is located, using historical and instrumental seismicity data (periods of return, frequency of exceedance…) and geological investigations (seismogenic structures, stratigraphy…). Seismic waves and appropriate ground motion attenuation relationships (from potential magnitude, seismic source to site distance) give free field normalised response spectra anchored to a peak ground acceleration (PGA). Design basis earthquake. Other ground motion indicators used. Seismic motions and accelerograms are produced in order to carry out transient analyses of buildings and components, complying spectral representation, coherency, duration…from available databases or synthetic methods.

Some basic dynamic principles for seismic analysis

The analysis of the Single degree of freedom (SDOF) elastic mechanical damped system gives important aspects of the expected features of any mechanical system subjected to seismic forced oscillations, and it also leads to define many usual terms. We present the role of inertial forces, the energy balance, the resonance for the natural period of the SDOF system, the dynamical amplification of the relative displacement, the decaying amplitude and loss angle according to the damping level and loss factor.

Displacement transfer function; solutions by means of Duhamel's integral; Fourier's transform and response spectra by maximal pseudo-accelerations against natural period are presented. Secondly, we present the dynamical linear behaviour of a continuous medium (eigenmodes), and its idealisation by a multi degrees of freedom system, the salient role of boundary conditions, the decomposition of dynamic solutions on truncated modal basis; differential displacements, energy transfer and possible coupling effects, with an illustration about the seismic isolation (dynamic filtering and additional damping).
Third, we introduce briefly the non-linear behaviour of the constitutive materials: its role in the energy balance and associated dissipation, the ductility and the ability to take up energy, the stiffness reduction by damage (concrete) and the consequential natural frequencies drop off.
The fourth topic concerns the soil behaviour under seismic loading: different kinds of waves, consequences of the stratigraphy (wave reflections), of the wave velocities variations in depth, of the internal dispersion. Linear equivalent approach, non-linearities, and inhomogeneity effects. Soil bearing capacity.
Finally, we present quickly several dynamical interactions:

- Soil-Foundation Interaction (SSI) introducing "radiation damping" and interface impedance, and their effect on structure seismic responses,
- Fluid-Structure Interaction (FSI), with corresponding added mass and damping, sloshing and its effect on internal vessel structures, tanks or spent fuel pools under seismic loading.

Main precepts for seismic design

Resonance and dynamic coupling and energy transfer. Frequency level and response transition from forces control to displacements control. Damping evaluation.
Available ductility and energy absorption, versus strength criteria (yielding, ratcheting…) to withstand to seismic solicitations. Damage non-linearities and frequency drop off. Appropriate plant layout. Mass distribution effects, 3D effects, structures pounding; differential displacements, soil settlements…

Available methods for seismic analysis and state-of-the-art engineering practice

Conventional seismic design procedures: Linear Modal-Spectral analysis from ground response spectra and deriving floor response spectra, modal responses combination rules. Usual analysis and model assumptions; stick-model with lumped masses versus 3D FEM model, according the case: buildings, components, equipments. Experimental qualification.
Periodic seismic re-evaluations: probabilistic safety assessment (PSA; scenarios, fault trees, anchoring vulnerabilities, missile risk…) and seismic margin assessment. Non-linear static or "push-over" analysis, behaviour factors. Best-estimate and non-linear transient dynamic analysis approach and seismic accelerograms. Different SSI methods, sub-structuring and seismic computations (frequency and time domains), in linear or non-linear range (base-mat uplift…). Important topics in the seismic margin evaluation.

Recent research and developments

Many research topics are investigated within the seismic community: we merely quote some of them. Models for seismic hazard and prediction of ground motion. Consideration of incoherency of earthquake motions in the Soil-Foundation Interaction analysis and non-linearities. Site effects and input motions. Probabilistic risk quantification and fragility studies.

Shaking table testing and new computational modelling needs (constitutive model improvements, for soil as for building, robustness and efficiency of numerical methods, uncertainties propagation…).

Better understanding of site behaviour, earthquake motion instrumentation should be laid on to record current dynamic behaviour, small and large earthquakes.

Seismic isolation bearings and other energy transfer devices for seismic mitigation: qualification and consequence on the seismic structural responses.

Concluding remarks and remaining challenges

Complexity of the seismic analysis; different objectives (design and re-evaluation, deterministic and probabilistic approaches for risk-informed evaluations…). Best estimate analysis and strengthening of the Nuclear Power Plant safety: need for site data, experimental testing, and appropriate numerical methods accounting for non-linearities, share of engineering methods and convergence of international standards, for both near- and far-field seismic input motions. Treatment of "defence in depth" safety approach. New design dispositions and seismic risk mitigation devices.

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