11 WCEE

Copyright © 1996 Elsevier Science Ltd
Paper No. 521. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

THE SEISMIC ANALYSIS OF VVER-1000 NUCLEAR POWER PLANT BUILDINGS FOR LIAONING SITE IN CHINA

Pentti Varpasuo
IVO International Ltd,
01019IVO, Finland

ABSTRACT

The object of this paper is to describe the methods and the results of the seismic analysis of the Category I buildings in the VVER-1000 NPP designed for the Liaoning site in the Peoples Republic of China. For the seismic response analysis the load was characterised with synthetic acceleration time histories and the stick models were developed for all investigated buildings. The foundation soil was a weathered rock and the soil structure interaction was accounted for by using frequency independent stiffness and damping constants for the foundation soil. For structural analysis of the plant buildings 3D-models were developed. The maximum floor accelerations calculated with the aid of stick models were applied in the 3D-models and appropriate seismic component combination rules were utilised. The seismic loads were combined with other loads and the stresses in the structures were solved. The results of the seismic response analyses of the plant buildings were the in-structure response spectra. The results of the 3D-analyses of plant buildings were the colour diagrams which gave the reinforcement amounts for all slabs and walls in the buildings.

KEYWORDS

Seismic response, response spectrum, 3D-model, stress analysis, reinforcement amount.

INTRODUCTION

This study reports the methodology used and the results obtained in the seismic design of the VVER-1000 nuclear power plant in Liaoning, China. The seismicity of the site was moderate and the excitation was defined with the aid of peak ground acceleration value and the prescribed ground response spectrum. The foundation was weathered rock and its classification was in the border between medium and hard soil condition. The task comprised of the modelling of all Category I buildings and of the seismic response analysis and of the stress analysis. The plant buildings to be analyzed were the reactor building, safety building, building for main steam isolation valves and diesel building. The first aim of the work at hand was to determine the in-structure acceleration response spectra for all buildings for the needs of equipment and component seismic analysis and design and the second aim was to carry out the stress analysis of the structures in the analyzed buildings and to determine the amount of reinforcement needed in the concrete.

SEISMIC EXCITATION

The intensity of the ground motion during the eartquake for the needs of this investigation is defined by the peak ground acceleration. Its frequency content is given by the ground response spectrum and its energy content is determined by the duration of ground shaking. The maximum horizontal ground acceleration amplitude in case of safe shut-down eartquake is 0.2 g. For the response spectra of the motion in the ground the spectra developed by USNRC (USNRC, 1973) are used. Figure 1 depicts the used ground response spectrum scaled to the appropriate value of the peak ground acceleration and corresponding to the value of 5% for the damping ratio. Using this target spectrum acceleration time histories with a given peak value and a given duration are obtained through numerical simulation (SIMQKE, 1976). The method used for the artificial motion generation is based on the fact that any periodic function can be expanded into a series of sinusoidal waves. With the iterative simulation algorithm the response spectrum calculated from the simulated acceleration time history is fitted with the target spectrum within a given margin. The duration of the simulated acceleration time history was 15 seconds. In Fig. 1 the fit of the spectrum calculated from the simulated motion is described with the target spectrum.

MODELLING TECHNIQUE

In seismic response analysis the mathematical modelling is essential. To predict the seismic response of structures subjected to the postulated design earthquakes mathematical models have to be developed to represent the structures and foundations. Using well established techniques the system of simultaneous differential equations representing the motion of the model is composed and solved for the structural response. The structures are designed to remain essentially elastic under the design seismic load and, consequently, the techniques of response analysis assume that the deformations remain small during the response history and the behaviour of the structure is assumed linearly elastic.

The coupling effects of the structural model with the foundation medium are accounted for using the methods of soil-structure interaction. These coupling effects become pronounced on a flexible soil when the shear wave velocity is less than 1100 m/s. In our case the soil is weathered rock and it is flexible enough to warrant the use of soil-structure interaction analysis. However, the simplified version of soil-structure interaction is adopted and the stiffness and damping coefficients representing the foundation soil are assumed to be frequency independent. In the following analysis two separate models for each investigated building are developed. The seismic response of the building is studied with the aid of stick model and the detailed stress analysis of the building is carried out using the true 3D-model of the building which includes shell and beam elements.

The stick models are set up using the following principles. Buildings are modeled as a system of lumped masses connected with each other by beams. The lumped masses are located at elevations of mass concentrations, such as floors. The beam elements are used to describe walls between different floors. Cross-section properties such as area, centroid, principal axes, moments of inertia and torsion constant for the beam elements are calculated according to the cross-sectional areas of the walls. All the beam elements are located vertically along the centre of rigidity and masses are lumped at the mass centre. Because there are some eccentrities between different floors, the multipoint constraints are used to describe horizontal rigid connections between the nodes of different beam elements. Also the nodes representing eccentric masses are connected to the beam elements by rigid links.

For the 3D-modelling following principles were complied with. Four noded quadrilateral shell elements capable to take also transverse shear forces into account and general beam elements were used to model the structures. Each node in the models had six degrees of freedom, three translations and three rotations. In developing the models all concrete floors, walls, columns and beams were included. The model was formed along the center lines of structures. Floors and walls were modeled by shell elements and the columns and beams by bar elements. The properties of the elements were determined according to the concrete material properties and the nominal dimensions of the structures. Figure 2 shows the 3D-analysis model of the interral structures of the reactor building.

SOIL STRUCTURE INTERACTION

In stick models used for the seismic response analysis the seismic excitation is applied to a big mass because the large mass method is used to excite the model according to prescribed time history. The big mass is connected by springs and dampers to the base of the structure. The springs and dampers represent the properties of the foundation soil. The spring and damping constants are calculated for three translations and three rotations according to the ASCE standard (ASCE, 1986). The spring and damping constants are frequency independent.

In the 3D-models the base level nodes were connected to the fixed boundary with three translational springs. The distributed spring constants were calculated so that their resultant values corresponded to the lumped parameter representation used with stick models.

SOLUTION METHODS

For seismic response analysis the mode superposition time history method was used. First the eigenvalues and modeshapes were calculated. The equations of motion were transformed to a space spanned by the modeshapes of the model. This transformation leads to a system of uncoupled second order differential equations in time. These differential equations can be solved in closed form for a given load and the results are the weights of the modeshapes as functions of time. With this information the time histories of the displacements, velocities and accelerations in the model can be calculated using the superposition of modes multiplied by the weights. On the basis of acceleration time histories of selected degrees of freedom the response spectra for these responses can be calculated.

The stress analysis with the aid of the 3D-models is performed statically. The maximum accelerations for each floor level of the model in three coordinate directions are multiplied by the tributary masses of the model in order to obtain the equivalent static presentation of the seismic loads in each coordinate direction. The maximum earthquake accelerations are obtained from dynamic analysis of the stick models. The three components of the earthquake load are combined using linear coefficients which are determined so that the combination rule is in accordance with the square root of the sums of squares rule (USNRC, 1976). Finally, the seismic loads are combined with the other relevant loads such as dead loads and live loads.

THE IN-STRUCTURE RESPONSE SPECTRA

The response spectrum for a given excitation time history is developed from the transient response of a series of simple oscillators. Each oscillator consists of a mass which is the connected by spring and damper to the vibrating base. The response of the oscillator is a function of two parameters: natural frequency and damping. The response spectrum is the curve of peak responses of these oscillators as a function of natural frequency. The damping of the oscillator is a parameter for the spectral curves.

The acceleration response spectra for each interesting floor level in three coordinate directions were generated for the Category I plant buildings (USNRC, 1978). The response calculations as well as the response spectra calculations were performed using MSC/NASTRAN program (MSC/NASTRAN, 1994). The length of the used response time history was 20 s and the increment of 1 millisecond between each calculation point for the spectra generation was used. The spectra were generated for damping values of 0,5%, 2% and 7% of the critical damping. In Fig. 3 the in-structure response spectra of the floor +13.20 of the control building are depicted.

THE 3D-STRESS ANALYSIS

The 3D-stress analyses were performed in order to design and proportion the reinforced concrete structures for the plant buildings. The most complicated load in the 3D-analyses was seismic load. It had three different components in coordinate directions and each of the components could have positive and negative signs or could be combined with both other components or with one other component or treated as acting alone. When all possible variants of the combinations were accounted for the total number of load cases rose to tens. The stress resultants from 3D-analyses were post-processed with concrete proportioning program IVODIM (Imatran Voima Oy, 1992). IVODIM is a design program for reinforced concrete structures. The dimensioning of the structures can be carried out in ultimate limit state and in the limit state of cracking. The program can handle thermal and mechanical loads and their combinations. In case of general shell elements the reinforcement is calculated for both surfaces of the elements and for two local coordinate directions. The design reinforcement amounts are the maximum values obtained when the dimensioning is performed for all loading cases. The results of IVODIM are presented in colour diagrams were reinforcement amounts in square millimetres per one meter width are given. Figure 4 shows a typical reinforcement diagram for a slab.

CONCLUSION

On the basis of the work performed following remarks can be made. The stick models are satisfactory way to model the nuclear power plant structures for seismic response calculations. The results obtained from the stick models can be used for the design of plant equipment as well as for designing the structures of the plant buildings. The 3D-modelling of the plant buildings is necessary for systematic design and proportioning of the structures for the multitude of load combinations. The automatic transfer of the data from structural analysis program to the post-processing design program is essential for the successful design process. In course of the design of the complicated shell structures of the plant buildings the effectiveness and versatility of the used program suite was demonstrated.

REFERENCES

USNRC, (1973), Regulatory Guide 1.60, Design Response Spectra for seismic Design of Nuclear Power Plants.

Massachusetts Institute of Technology, (1976), SIMQKE, A Program for Artificial Motion Generation, User's Manual and Documentation.

ASCE STANDARD 4-86, (1986), Seismic Analysis of Safety-Related Nuclear Structures, American Society of Civil Engineers.

USNRC, (1976), Regulatory Guide 1.92, Combining Model Responses and Spatial Components in Seismic Response Analysis.

USNRC, (1978), Regulatory Guide 1.29, Seismic Design Classification.

Mac Neal-Schwendler Corporation, (1994), MSC/NASTRAN User's Guide, Version 68.

Imatran Voima Oy, (1992), IVODIM, Design Program for Reinforced Concrete Structures, Internal Report.

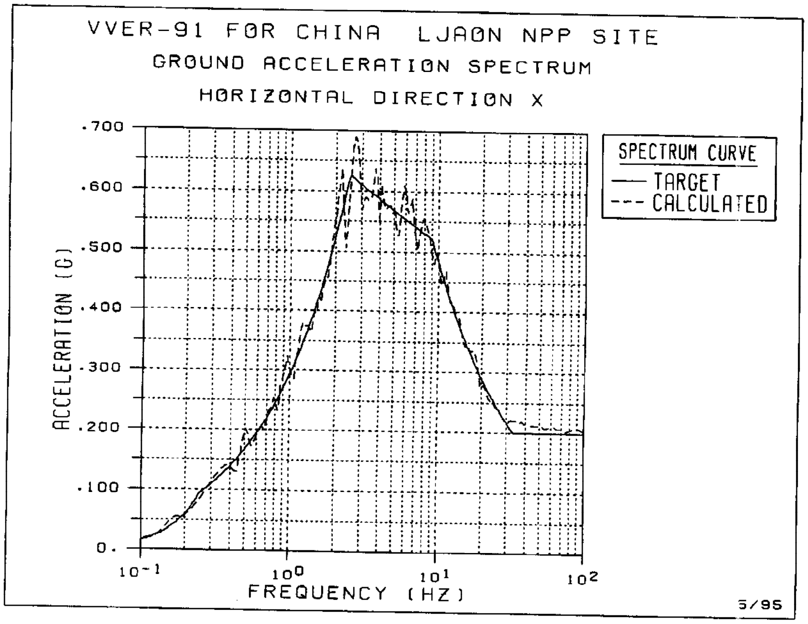


Fig. 1 The target ground acceleration spectrum and the spectrum of the simulated motion.

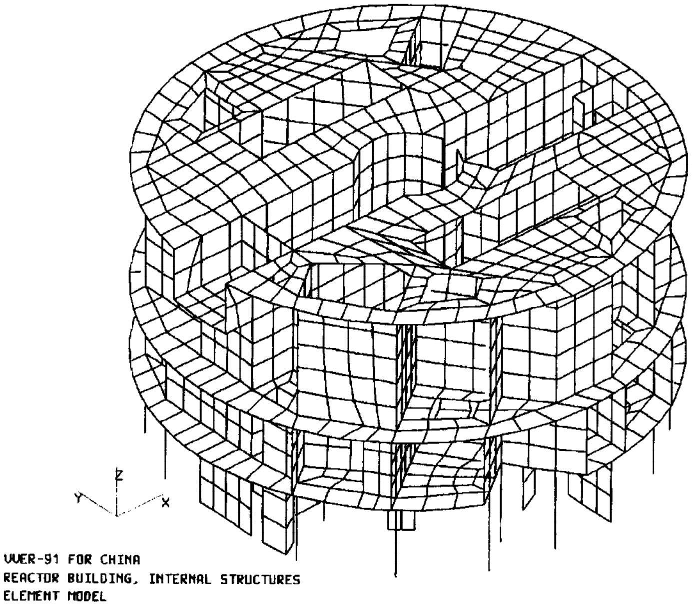


Fig. 2 The 3D-analysis model of the internal structures of the reactor building.

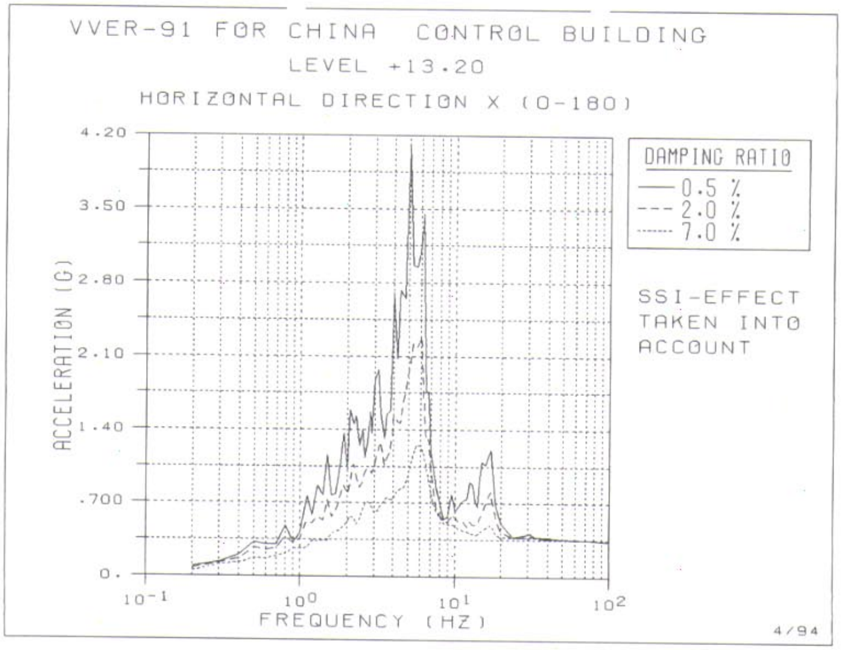
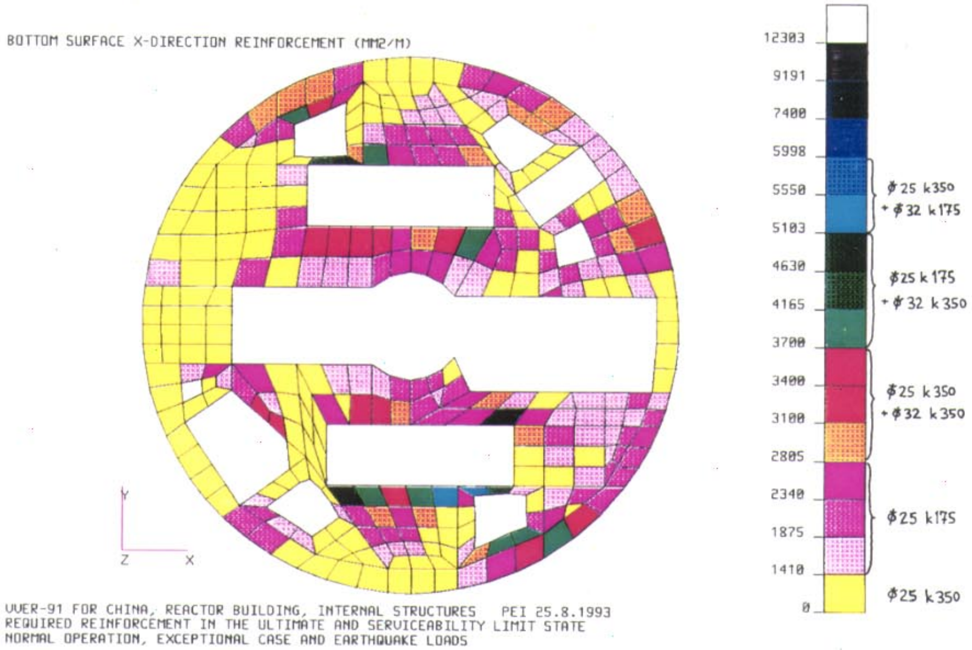

VVER-91 FOR CHINA CONTROL BUILDING
LEVEL +13.20
HORIZONTAL DIRECTION X (0-180)

Fig. 3 The in-structure response spectra of the level +13.20 of the control building.


BOTTOM SURFACE X-DIRECTION REINFORCEMENT (MM2/M)

VVER-91 FOR CHINA, REACTOR BUILDING, INTERNAL STRUCTURES PEI 25.8.1993
REQUIRED REINFORCEMENT IN THE ULTIMATE AND SERVICEABILITY LIMIT STATE
NORMAL OPERATION, EXCEPTIONAL CASE AND EARTHQUAKE LOADS

Fig. 4 The diagram for the reinforcement amounts in X-direction of the bottom surface of the main operational floor of the reactor building.