



Dynamic behavior of VVER-440/230 Novovoronezh under earthquake loading

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ABSTRACT

In order to evaluate the structural behavior and the seismic stability of the main building complex during earthquake loading, dynamic analyses were performed using detailed mathematical models of the coupled vibrating structures (reactor building, turbine hall, ventilation building, longitudinal and transverse service building). The structural response for characteristic regions of the buildings as well as the forces in all relevant regions of the structures were derived and evaluated.

INTRODUCTION

There are four first generation VVER-440 units at Novovoronezh constructed 1962. Two of the units (1 and 2) stop the operation in 1979. The investigation presented here relates to Units 3 and 4 which were designed in 1967. Neither of these units were primarily designed for earthquake loading conditions. The aim of the investigations, performed within the TACIS project NUCRUS 9401, was to evaluate the seismic stability as well as the dynamic response behavior of these units during a site-specific earthquake predicted for the site Novovoronezh.

In order to analyze the dynamic behavior of the coupled vibrating system of four interconnected buildings and interacting through the soil, an appropriate three-dimensional mathematical model was generated [3].

The capabilities of the soil at the site were represented by equivalent stiffness and damping obtained from the impedance function calculated in advance [2] and distributed appropriately below the discretized foundations. This ensured that not only the elastic deformability of the soil medium but also is radiation damping to absorb translational, rocking and torsional motion and hysteretic damping would be properly accounted for. The calculations were performed in the time domain.

A set of artificial time histories acting simultaneously was used as excitation (Figure 3). The maximum acceleration for the horizontal direction X1 and X2 was defined [1] as 0.106 g and 0.055 g for the vertical direction.

The modal damping was limited in accordance with international standards.

DESCRIPTION OF THE STRUCTURE

The main building (Figure 1) of each of the twin units is designed as a rectangular, reinforced-concrete/steel structure measuring approximately 60 m in length and 51 m in width. It is supported by a 1.20 m thick foundation slab.

The bottom of the building foundations is located approximately 3.0 m below plant grade. In view of the thickness of the foundation slab - 1.20 m - this results in a total height of approximately 43.0 m of which 39.0 m are above plant grade. The load bearing and stiffening members mostly comprise walls and floors. Up to elevation 10.3 m, the structure of the main building represents a monolithic concrete block. The turbine house which is a concrete-frame structure and has separate foundations is coupled to the main building (by means of an intermediate building). The turbine house comprises eleven concrete frames with single footings. The frames are stiffened by longitudinal and cross trusses.

The electrical building (longitudinal galleries) which houses important components is located between the main building and the turbine house. The control room and electrical equipments are located in the transversal galleries. This transversal gallery has also single footings.

The weight of the models is made up by the actual weight of the structure, by the weight of the important components, the weight of small electrical and mechanical components and non-dead weights. The weight of the primary circuit, the reactor pressure vessel and another heavy components were introduced into the model as concentrated masses. Small weights and non-permanent weights were considered to increase the specific weight of the corresponding floors. The total weight of the model of the coupled vibrating structures is approximately 700000 kN.

MATHEMATICAL MODEL

In order to investigate the dynamic behaviour of the main building complex (Figure 1), a complete three-dimensional model was generated [3]. The main building was idealized by means of a 3D plate and beam elements model (Figure 2). The type and degree of discretization of the model (about 15000 DOF) were such as to guarantee that the frequency range corresponding to the relevant excitations could be analyzed, i.e. that the structural vibration at the locations at which the components are installed or at which they are anchored to the structure would be realistically represented.

This yielded an appropriate element size which had to comply with regard to the adaptation the nodal structure to the axes of the main walls and the floors. The structural cells and walls determining the load-carrying capacity of the reactor building formed the basis governing the structure of the model. Small openings and recesses were either neglected or accounted for by adapting the stiffness and mass of the associated floor or walls elements accordingly.

In distributing the masses, the loads imposed by the mechanical and electrical components were also taken into account in addition to the dead weights of the building structure. The dynamic behavior of the foundation which is situated on a horizontally layered, viscoelastic halfspace was represented by complex, frequency-dependent impedance functions. These functions have been calculated for the six degrees of freedom of the rigid foundation. Embedment of the building in the soil was ignored.

The global soil stiffness and damping underneath the reactor building were derived from the impedance functions for the following soil conditions: G_{\max} , G_{ave} and G_{\min} . The stiffness and the damping of the soil were tuned to the fundamental frequencies of the coupled soil-structure system and were assumed to be frequency-independent. These frequency-

independent springs and dampers were distributed through all the nodal under the foundation slab.

DYNAMIC CHARACTERISTIC

The eigenfrequencies and modes were calculated for the static as well as strain-adapted shear modulus [4]. The modal values for G_{ave} are shown in Table 1. The final strain-adapted values were obtained by several modification steps of stiffnesses obtained from the corresponding impedance function and additional eigenvalue runs.

The fundamental eigenfrequencies are about 3.24 Hz and 3.45 Hz in the horizontal direction X1 and X2 and about 5.0 Hz in the vertical direction (Figures 5 and 6). The lowest frequency of the steel structure of the reactor hall in the X1 direction is about 0.98 Hz (Figure 4).

It was found that the sum of the modal masses up to 20 Hz constitutes about 99 % of the total actual weight and that therefore the frequency range relevant to the seismic loading condition is adequately enveloped.

In modal analyses, damping is considered in the form of modal damping. On the basis of the variations in the structural damping characteristics of the building and the soil, the damping values of the individual modes (modal damping) are calculated by applying a weighting function proportional to the deformation energy. In accordance with KTA Safety Standard 2201.3 (Ref. [3]), the modal damping values thus obtained were limited to 15 % for horizontal and rocking vibration, and to 30 % for vertical vibration.

CHARACTERISTIC RESULTS

The structural response were calculated for selected locations (Figure 1). The main building structure is shown in form of accelerations response spectra (Figures 7 and 8). In addition, the forces in the structural members were derived and evaluated in accordancy with International Standards [6]. Figures 10 and 11 shows overstressed ($F_y > 335 \text{ N/mm}^2$) regions of the steel structures (mainly the roofs of the reactor hall and turbine house). The figure clearly shows that only few regions the allowable stresses were exceeded (by max. 10 %) in only a small number of regions. Similarly, the bearing capacity of the concrete columns and beam were evaluated in the overloaded regions ($M_{max} > 1500 \text{ kNm}$) and are shown in Figures 12 and 13.

CONCLUSIONS

The dynamic behavior as well as the response results are quite similar to those of a other VVER-440/230 type NPPs operating on soft site conditions. With regard to the rather low seismic capacity however, (the original design did not consider earthquake loading effects at all) some regions of the steel and concrete structures seems to be slightly overloaded.

In order to be able to decide if some retrofit measures are required more detailed investigation have to be performed. With regard to the rather low level of dynamic response in the characteristic regions, major upgrading measures for components and systems do not appear to be required.

REFERENCES

- [1] Soil Modeling and Site Specific Input Motion
Subtask 2.5
ISMES Report Doic. Rat-STA-1155/96

- [2] Dynamic Calculations of VVER-440 NPP Novovoronezh
Structures Against Seismic Events Impedance Functions
Siemens Report KWU NDA2/96/E0231

- [3] Mathematical (3D) Model and Frequency-Independent Soil Parameters
of the Min Building Complex of the VVER 440 NPP Novovoronezh
Siemens Report KWU NDA2/96/E0427

- [4] Dynamic Characteristics of the Main Building Complex of the VVER 440 NPP
Novovoronezh
Siemens Report NDA2/96/E0468

- [5] STRUDYN
General Computer Program for Linear-Elastic Static and Dynamic Analysis of
Structures
USER Manual, Version 3/91

- [6] EUROCODE 2 - 8

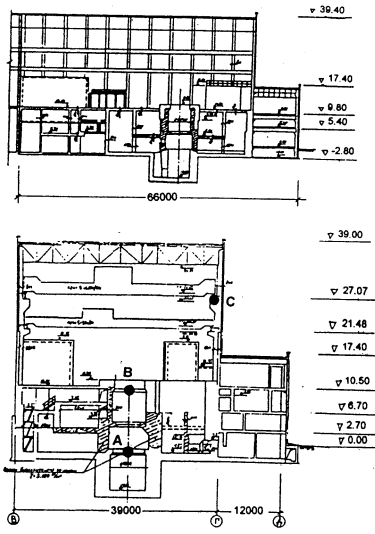


Fig. 1 Constructional Concept VVER440/230 NOVovorONESH

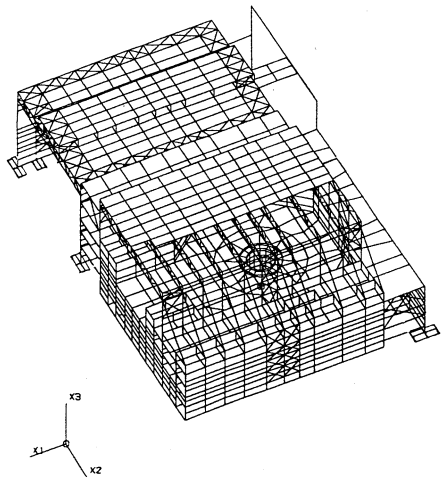


Fig. 2 Mathematical Model

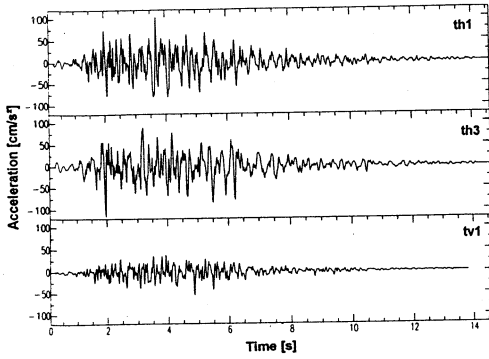


Fig. 3 Artificial Time Histories, Site NOVOVORONESH

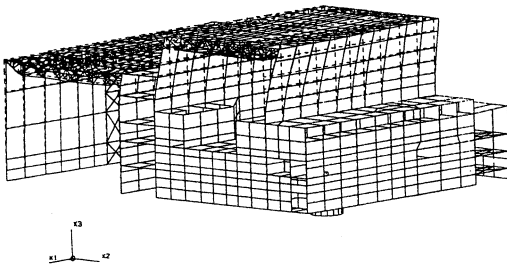


Fig. 4 Eigenmode Nr.1, 0.98 Hz, Horizontal X1-Direction

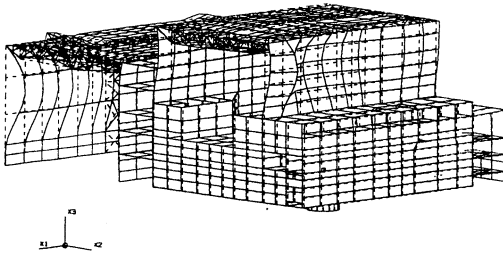


Fig. 5 Eigenmode Nr.68, 3.45 Hz, Horizontal X2-Direction

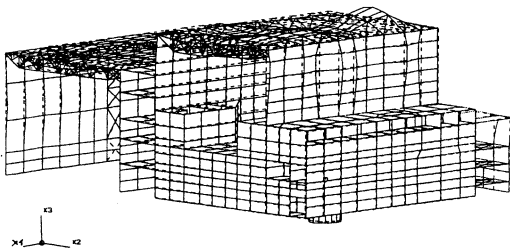


Fig. 6 Eigenmode Nr.100, 5.02 Hz, Vertical Direction

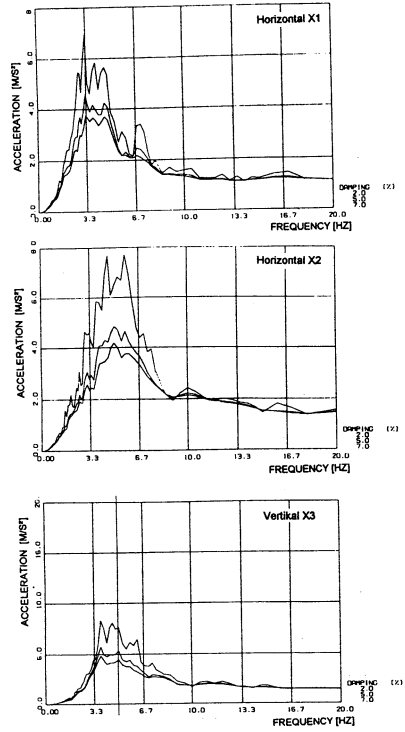


Fig. 7 Dynamic Response on the Foundation Level (A)

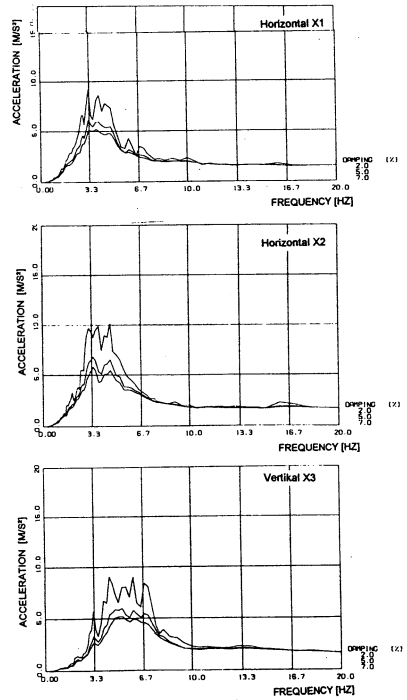


Fig. 8 Dynamic Response on Elevation 10.30 m (B)

Tab. 1 Dynamic Characteristics, G₀

MODE	FREQUENZ	MAX	MODALE		GEWICHTE		X3	DAERPFING (%)							
NR	(1/SE)	DOF	X1	X2	X1	X2		MODAL	ETA						
1	0.98	7072-2	944.83	53242.13	2.12	7.86	7.86	56	2.61	6023-1	0.29	0.60	0.01	7.00	7.00
2	1.20	6035-1	17243.45	2305.10	0.03	7.87	7.87	53	2.56	6223-1	4.18	5.67	0.27	7.00	7.00
3	1.30	3064-3	0.23	0.22	65.69	7.00	7.00	54	2.61	5129-1	0.01	0.23	0.26	7.00	7.00
4	1.47	6223-1	2167.35	155.18	38.02	7.18	7.18	59	2.62	5523-1	1.01	5.10	0.12	7.00	7.00
5	1.56	5546-3	17.54	588.19	9397.29	7.08	7.08	50	2.62	5823-1	0.00	0.01	0.02	7.00	7.00
6	1.62	6346-1	0.88	0.05	0.00	7.00	7.00	61	2.64	5123-1	36.39	334.07	10.26	7.03	7.03
7	1.62	6345-1	0.00	0.00	0.00	7.00	7.00	62	2.71	7347-3	47.28	0.14	2.82	7.00	7.00
8	1.63	5946-3	696.60	68.40	33.43	7.07	7.07	63	2.62	8281-1	15.40	302.72	977.59	7.11	7.11
9	1.64	6347-1	3.08	0.16	0.01	7.00	7.00	64	2.18	5123-1	14828.34	9705.22	58.69	7.67	7.67
10	1.66	6343-1	21.33	1.48	0.16	7.00	7.00	65	3.12	3231-2	10471.60	65230.55	196.35	12.55	12.55
11	1.67	6350-1	157.89	8.36	0.52	7.01	7.01	66	3.20	8521-1	23302.83	11068.01	124.25	9.50	9.50
12	1.69	6349-1	24.53	0.91	0.00	7.00	7.00	67	3.24	8481-1	203605.40	8709.04	474.31	16.12	16.12
13	1.71	6347-1	247.15	24.24	11.86	7.01	7.01	68	3.45	3231-2	125160.02	504.86	16.50	15.00	15.00
14	1.71	6347-1	4.40	56.78	259.12	7.06	7.06	69	3.49	6223-1	18398.29	16937.82	97.35	16.53	16.53
15	1.80	5846-3	324.52	58.08	103.80	7.04	7.04	70	3.53	3330-2	42430.40	115158.47	322.11	13.42	13.42
16	1.82	6246-3	123.10	1721.24	1103.80	7.08	7.08	71	3.70	3231-2	47.08	3676.65	83.57	7.48	7.48
17	1.88	5046-3	671.04	528.37	233.45	7.09	7.09	72	3.75	8441-1	640.03	6524.10	474.35	7.58	7.58
18	1.92	7385-3	667.10	3053.40	4148.24	7.16	7.16	73	3.80	7052-3	5722.40	335.92	0.28	7.35	7.35
19	1.93	7385-3	629.04	2310.93	90.82	7.17	7.17	74	3.80	7052-3	611.60	1559.20	26.77	7.50	7.50
20	1.95	5029-1	10.15	2.13	1.95	7.00	7.00	75	3.86	4001-2	6.11	60.00	0.67	7.43	7.43
21	1.95	6229-1	7.40	1.85	0.02	7.00	7.00	76	3.91	4005-2	26.41	252.97	0.87	7.43	7.43
22	1.95	5023-1	0.27	0.32	93.12	7.02	7.02	77	4.00	4009-2	232.42	1504.49	1.95	7.48	7.48
23	2.00	5723-1	0.46	0.31	0.62	7.00	7.00	78	4.01	4001-2	393.75	1973.58	6.56	7.47	7.47
24	2.01	5929-1	0.00	0.38	0.06	7.00	7.00	79	4.01	4001-2	393.75	1973.58	6.56	7.47	7.47
25	2.02	4043-2	55.15	5373.65	392.76	7.20	7.20	80	4.05	6421-1	865.77	1566.60	165.31	7.36	7.36
26	2.02	5221-1	3.43	235.09	1.92	7.00	7.00	81	4.05	4003-2	122.75	43.54	6.75	7.39	7.39
27	2.03	5849-1	0.89	28351.43	2436.15	8.03	8.03	82	4.07	4001-2	23.86	1599.76	34.38	7.47	7.47
28	2.04	5829-1	1.21	0.27	0.49	7.00	7.00	83	4.09	4011-2	0.80	63.41	0.09	7.35	7.35
29	2.04	5829-1	0.15	0.43	0.83	7.00	7.00	84	4.12	8421-1	150.80	1881.99	2.59	7.25	7.25
30	2.07	5829-1	0.36	0.16	0.20	7.00	7.00	85	4.13	6011-2	17.00	21.15	0.16	7.33	7.33
31	2.07	7390-3	2998.27	3429.03	808.45	7.23	7.23	86	4.17	4002-2	7.50	31.05	1.21	7.30	7.30
32	2.08	5129-1	246.96	38.40	5.14	7.01	7.01	87	4.21	4008-2	1.56	42.29	0.07	7.18	7.18
33	2.08	6029-1	306.88	1.43	0.15	7.01	7.01	88	4.23	3224-2	1394.93	5835.93	24.28	8.52	8.52
34	2.09	6403-1	18732.26	447.59	55.72	7.89	7.89	89	4.27	6237-5	0.54	3.93	0.89	7.67	7.67
35	2.10	5729-1	0.18	23.72	2.29	7.00	7.00	90	4.28	4007-2	0.44	6.08	0.33	7.22	7.22
36	2.15	6405-1	20991.21	982.71	786.98	7.81	7.81	91	4.29	4421-1	2422.07	8017.89	642.39	8.56	8.56
37	2.21	6160-1	1879.18	136.71	645.18	7.14	7.14	92	4.48	6237-1	95.85	49.34	42.13	7.08	7.08
38	2.29	6229-1	2612.93	1825.17	226.17	7.40	7.40	93	4.49	6237-1	371.12	581.46	231.11	7.46	7.46
39	2.31	5746-3	81.69	88.20	19.98	7.02	7.02	94	4.58	6237-1	2286.72	481.78	2485.47	9.07	9.07
40	2.32	7386-3	1141.28	18.46	110.99	7.04	7.04	95	4.60	7772-2	446.54	6058.53	432.10	7.79	7.79
41	2.34	6403-1	24.97	1.49	1.20	7.00	7.00	96	4.65	6237-1	1363.11	2768.89	101.28	7.44	7.44
42	2.35	6405-1	0.46	0.01	0.00	7.00	7.00	97	4.71	3229-2	83.57	116.69	612.89	7.30	7.30
43	2.35	6405-1	0.04	0.04	0.04	7.00	7.00	98	4.78	6231	3762.46	4660.76	77.53	8.01	8.01
44	2.35	6410-1	13.26	0.21	0.08	7.00	7.00	99	4.87	6109-3	95.44	275.52	703.65	7.44	7.44
45	2.35	6406-1	3.21	0.00	0.00	7.00	7.00	100	5.01	7403-3	806.19	142.68	14383.81	34.02	34.02
46	2.35	6407-1	7.22	0.07	0.02	7.00	7.00	101	5.11	3222-2	205.07	46.77	19293.67	9.71	9.71
47	2.39	6403-1	19083.88	122.84	56.08	7.91	7.91	102	5.16	7403-3	896.70	115.11	6684.83	15.14	15.14
48	2.41	6403-1	10104.70	2.77	38.96	7.50	7.50	103	5.22	7403-3	817.10	0.22	7284.27	8.10	8.10
49	2.52	7379-1	937.18	0.15	0.11	7.58	7.58	104	5.23	7409-3	1963.10	28.88	10520.87	11.11	11.11
50	2.53	6403-1	20500.10	17.14	384.65	8.11	8.11	105	5.29	7411-3	803.72	4228.64	4446.18	8.07	8.07

Tab. 2 Global Soil Stiffness and Damping

GN MIN						
DIR	X	Y	Z	XX	YY	ZZ
Ko [kN/m]	25.0E6	26.2E6	66.0E6	23.0E9	36.0E9	23.0E9
Ko [kN/m]	20.0E6	22.2E6	66.0E6	16.2E9	21.7E9	16.4E9
D [%]	40	40	70	30	40	20

GA AVE						
DIR	X	Y	Z	XX	YY	ZZ
Ko [kN/m]	37.0E6	38.0E6	93.0E6	35.0E9	53.0E9	34.0E9
Ko [kN/m]	35.0E6	30.0E6	93.0E6	23.8E9	31.6E9	26.0E9
D [%]	40	40	70	30	40	20

GX MAX						
DIR	X	Y	Z	XX	YY	ZZ
Ko [kN/m]	55.0E6	57.0E6	136.0E6	51.0E9	78.0E9	51.0E9
Ko [kN/m]	45.8E6	48.2E6	136.0E6	35.7E9	47.6E9	38.1E9
D [%]	40	40	70	30	40	20

Tab. 3 Stiffnesses of Separated Foundations

Dimension	Horizontal (x10 ⁶)	Vertikal (x10 ⁶)	Rocking (x10 ⁶)	Torsional (x10 ⁶)
3.5 x 5	0.54	0.63	0.032	0.012
1.5 x 4	0.32	0.37	0.100.023	0.094
4 x 4	0.52	0.61	0.21	0.30
3 x 4	0.45	0.52	0.170.11	0.20
2.5 x 2.5	0.32	0.37	0.052	0.073
1 x 2	0.18	0.21	0.0160.005	0.016
3 x 3	0.36	0.45	0.09	0.13
2.5 x 3	0.35	0.41	0.080.06	0.1
1 x 1	0.13	0.15	0.003	0.005
3.4 x 3.4	0.44	0.52	0.13	0.18
2 x 2	0.28	0.30	0.03	0.04
0.75 x 0.75	0.10	0.11	0.001	0.001
7.0 x 7.0	3.12	4.58	0.0199	0.051

The stiffnesses for G_{max} and G_{ave} are obtained multiplying the values from G_{min} by a factor equal to 2 and 0.5 respectively.