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3D ANALYSIS AND DESIGN OF THE CONTAINMENT FOR TIANWAN NUCLEAR POWER PLANT

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ABSTRACT

This paper reports the design of VVER-91 type Tianwan nuclear power plant in China. The reactor building consists of the outer containment, inner containment, internal structures and base slab with the tendon gallery. Inner containment is pre-stressed concrete shell structure that consists of a cylindrical part and a hemispherical dome. Inner surface of the containment is covered with a 6 mm thick carbon steel plate to secure the tightness. Inner containment is pre-stressed with 50 vertical tendons in two groups and 70 hoop tendons in two groups anchored in buttresses on opposite sides of the shell.

As a result of the analysis the concrete and tendon stresses were checked against the ASME allowances for all load combinations stipulated by ASME. Also the required amounts of longitudinal and transversal reinforcement were calculated as maximums from all investigated load combinations according to stipulations of ASME. The reinforcement amounts were depicted in color maps giving the needed longitudinal reinforcement cross-section area in square millimeters per meters width in both surfaces of the shell and in to mutually perpendicular directions and the needed transversal reinforcement in square millimeters per unit area of the shell.

INTRODUCTION

The purpose of the reactor containment building is to protect the environment against leakage of the primary circuit and to protect the environment against direct radiation of the primary circuit. On the other hand the purpose of the building is to protect the primary circuit against external hazardous events.

The task in this assignment was to perform the final design of a dry prestressed concrete containment structure for a pressurized water reactor. The structure under consideration is a double containment. The inner containment is a prestressed concrete structure consisting of a flat base mat, a cylindrical shell, and a hemispherical dome. The outer containment is a reinforced concrete structure consisting of a cylindrical shell with a flat top dome.

In this design task, the final detailed design of the inner containment under the criteria given by the ACI 359-95 Code [1] was carried out. The material characteristics of concrete and reinforcing steel were derived according to the Russian standard for concrete and reinforced concrete structures [2]. The work was performed in several stages as follows:

1. Initial proportioning of the containment using a rational design approach developed basic prestressing and reinforcement requirements, and thickness of the concrete structure. The prestressing requirements were given by the type, number, and spacing of the tendons. The thickness of the cylinder wall and dome was chosen to be 120 cm and 100 cm, respectively. Finite element analysis of the containment shell was also performed during this initial phase.
2. Evaluation of the final prestressing forces was based on specific prestressing system, final layout of all containment penetrations and corresponding tendon duct routing. The forces were calculated for the initial prestress and for the end of the design lifetime after 40 years.
3. Finite element analysis and design was made for the prestressed concrete containment shell, excluding the base slab, which has been designed in the previous design task. However, in the integral finite element model to analyse the load effects to the inner containment shell, also the foundation soil, base slab, outer containment, internal structures with main equipment and the prestressing tendons were included in the calculation model. In this phase the reinforcement requirements were developed and the capacity of the tendons was verified.
4. Local finite element model was developed for the buttress area to establish the reinforcement requirements near the anchors of the horizontal tendons.
5. Analysis and design of the steel liner plate and the supporting structures of the polar crane and accumulator tanks of emergency core cooling system.

DESCRIPTION OF STRUCTURE

The reactor building determines the location of the power plant. The safety building, the auxiliary building, the control building and the steam cell are joined to the reactor building.

The reactor building consists of the outer containment, the inner containment, the internal structures and the base slab with the tendon gallery. A general view of the structures and components of the reactor building can be seen in the layout drawings. The concrete structures are presented in the working drawings.

The outer containment is a conventionally reinforced shell structure that consists of a cylinder part and a flat dome. The outer diameter of the cylinder is 51.2 m and the top of the dome is at level +74.20. The thickness of the outer containment is 0.6 m both in the cylinder part and dome.

The internal structures are conventionally reinforced concrete structures that consist of a reactor pit, pools for fuel handling and reactor internals service, vertical walls and columns and intermediate floors at levels +16.00, +22.50 and +34.00. The internal structures are isolated by a clearance of 200 mm from the cylinder wall of the inner containment. The thickness of the internal structures varies from 0.2 m to 2.6 m and the median value is 1.2 m. Both the outer and inner containments and the internal structures are based on a round concrete base slab, which is founded directly on the bedrock. The base slab is a conventionally reinforced massive concrete structure that is divided into two layers by the base liner. The both containments are supported on the lower part of the base slab and the internal structures are supported on the upper part of the base slab. In the centre region of the upper part of the base slab there is a big tooth that is in a hole of the lower part of the base slab. The aim of the tooth is to prevent sliding between the two layers of the base slab under seismic conditions.

The top of the upper part of the base slab is at level +8.00 and the bottom of the lower part of the base slab is at level +4.00. The thickness of the lower base slab is 3.0 m except in the centre region 1.0 m. The thickness of the upper base slab is about 0.8 m in the outer region and about 2.8 m / 1.8 m in the centre region. The diameter of the base slab is 51.2 m.

The ring-shaped tendon gallery is situated under the base slab and centred under the inner containment. The base slab of the tendon gallery is at level +0.80 and this is the lowest floor in the reactor building. The thickness of the base slab of the tendon gallery is about 1.0 m and the thickness of the outer and inner walls are 0.6 m and 1.0-2.0 m, respectively.

CHARACTERISTICS OF MATERIALS

The grade of concrete for the design of the reactor building is B25 according to the Russian concrete classification given in the building code [2], except in the inner containment where the grade of concrete is B45. Corresponding material properties according to the ACI 349-97 [3] for the concrete of grades B25 and B45 are given in Table 1. The allowable compression stresses for concrete according to the ACI 359-95 [1] are presented in Tables 2 and 3 for service and factored loads, respectively. Concrete tensile strength is assumed to be zero.

Table 1 Characteristics of Concrete, MPa

Notation	Description	Grade B25	Grade B45
f_c'	Specified compressive strength of concrete	20.8	37.5
E_c	Modulus of elasticity of concrete	21 600	29 000
ν_c	Poisson's ratio of concrete	0.2	0.2
α_c	Coefficient of thermal expansion of concrete	$1.0 \cdot 10^{-5}$ /°C	$1.0 \cdot 10^{-5}$ /°C

Table 2 Allowable compression stresses for concrete for service loads, MPa

Notation	Classification	Type of Force	Notes	Grade B25	Grade B45
$0.30 f_c'$	Primary	Membrane		6.2	11.2
$0.35 f_c'$	Primary	Membrane	3) or 4)	7.3	13.1
$0.40 f_c'$	Primary	Membrane	3) and 4)	8.3	15.0
$0.45 f_c'$	Primary	Membrane plus Bending	2)	9.4	16.9
$0.45 f_c'$	Primary plus Secondary	Membrane	1)	9.4	16.9
$0.60 f_c'$	Primary plus Secondary	Membrane plus Bending	1) and 2)	12.5	22.5

1) The primary portion of this calculated stress shall not exceed the allowable stress applicable when primary stress acts alone.
2) The membrane portion of this calculated stress shall not exceed the allowable stress applicable when membrane stress acts alone.
3) At initial prestress.
4) Sections with radial tension reinforcement.

Table 3 Allowable compression stresses of concrete for factored loads, MPa

Notation	Classification	Type of Force	Notes	Grade B25	Grade B45
$0.60 f_c'$	Primary	Membrane		12.5	22.5
$0.75 f_c'$	Primary	Membrane plus Bending	2)	15.6	28.1
$0.75 f_c'$	Primary plus Secondary	Membrane	1)	15.6	28.1
$0.85 f_c'$	Primary plus Secondary	Membrane plus Bending	1) and 2) and 3)	17.7	31.9

1) The primary portion of this calculated stress shall not exceed the allowable stress applicable when primary stress acts alone.
2) The membrane portion of this calculated stress shall not exceed the allowable stress applicable when membrane stress acts alone.
3) The maximum allowable primary-plus-secondary membrane and bending stress of $0.85 f_c'$ corresponds to a limiting strain of 0.002.

A-III hot rolled ribbed bars according to the Russian code [2] were considered for principal nonprestressed reinforcement in the reactor building. Strength and elastic characteristics for the reinforcing steel of grades A-I and A-III are given in Table 4. The allowable stresses for the reinforcing steel according to the ACI 359-95 [1] are presented in Table 5.

Table 4 Characteristics of reinforcing steel, MPa

Notation	Description	Grade A-I	Grade A-III
f_y	Specified yield strength of reinforcement	235	390
E_s	Modulus of elasticity of reinforcement	210 000	200 000
α_s	Coefficient of thermal expansion	$1.0 \cdot 10^{-5}$ /°C	$1.0 \cdot 10^{-5}$ /°C

Table 5 Allowable stresses of reinforcing steel for service and factored loads, MPa

Notation	Description	Grade A-I	Grade A-III
$0.50 f_y$	Service loads, tension and compression	117.5	195.0
$0.90 f_y$	Factored loads, tension and compression	211.5	351.0

Prestressing tendons are Freyssinet type tendons consisting of 55 strands of 15.7 mm nominal diameter, made of high strength steel SUPER St 1630/1860. Nominal cross-section area of a tendon is 8250 mm^2 (= $55 \cdot 150$) and nominal mass per metre is 65 kg/m. Strength and elastic characteristics for the prestressing steel is given in Table 6. The allowable tensile stresses for the prestressing steel according to the ACI 359-95 [1] are presented in Table 7.

Table 6 Characteristics of prestressing steel, MPa

Notation	Description	SUPER St 1630/1860
f_{pu}	Specified tensile strength of tendon	1860
f_{py}	Specified yield strength of tendon, 1 % strain	1630
E_p	Modulus of elasticity of tendon	199 000
α_p	Coefficient of thermal expansion of tendon	$1.0 \cdot 10^{-5}$ /°C

Table 7 Allowable tensile stresses of prestressing steel, MPa

Notation	Description	SUPER St 1630/1860
$0.80 f_{pu}$	During stressing, at anchor point	1488
$0.73 f_{pu}$	Immediately after anchoring, at anchor point	1358
$0.70 f_{pu}$	Immediately after anchoring, average stress	1302
$0.90 f_{py}$	Factored loads	1467

INITIAL PROPORTIONING

The containment is to be designed so that it essentially remains in compression under service and structural integrity test load cases with a reasonable margin. The minimum effective prestress force in the containment structure at the end of the design lifetime is set to be 1.25 times the design pressure [4].

The initial proportioning of the tendons of the prestressed concrete containment was made using spreadsheet application. The main results of the initial proportioning are collected in Table 7.

Table 8 Summary of the results of the containment design based on initial proportioning

		CYLINDER / hoop	**CYLINDER / vertical**	**DOME / hoop**	**DOME / vertical**	**Unit**
DESIGN FORCES	F	11,00	4,79	2,50	4,86	[MN/m]
PRESSURIZATION EFFECT	fc	9,17	4,84	5,38	5,38	[MN/m2]
Tendon stress increase	fc*Es/Ec	62,90	33,21	36,88	36,88	[MN/m2]
plus Poisson effect	Δf	56,26	20,63	29,51	29,51	[MN/m2]
STRESS OF TENDONS						
Max. average stress after tensioning	fmax	1084,76	1381,51	1088,76	1326,72	[MN/m2]
Min. average stress after 40 years	fe	913,34	1237,74	854,97	847,72	[MN/m2]
plus tendon stress increase	fe + Δf	969,60	1258,38	884,48	877,22	[MN/m2]
AREA OF TENDON	F/(fe+Δf)	11345	3806	2830	5538	[mm2/m]
NUMBER OF TENDONS	N	56,66	16,38	6,37	23,83	[-]
SELECTED NUM. OF TENDONS	**N**	**57**	**25**	**13**	**25**	[-]
SPACING OF TENDONS	S	0,74	1,42	1,43	1,42	[m]
SELECTED AREA	area/S	11414	5810	5772	5810	[mm2/m]
MEMBRANE FORCES						
*** Min. average stress after 40 years without pressurization effect**						
Apex of dome					4,89	[MN/m]
45° on dome, vertical dome tendon only					5,91	[MN/m]
45° on dome, vertical and hoop dome tendon				2,49	3,00	[MN/m]
Springline		10,42	7,43	2,49	3,78	[MN/m]
Base of cylinder		10,42	7,19			[MN/m]
*** Max. average stress after tensioning without pressurization effect**						
Apex of dome					5,41	[MN/m]
45° on dome, vertical dome tendon only					6,44	[MN/m]
45° on dome, vertical and hoop dome tendon				3,17	3,30	[MN/m]
Springline		12,38	7,96	3,17	4,05	[MN/m]
Base of cylinder		12,38	7,72			[MN/m]
THICKNESS REQUIREMENTS						
Net thickness		0,94	0,74	0,75		[m]
Gross thickness		1,26		1,12		[m]
SELECTED STRUCTURE		**1,20**		**1,00**		[m]

TENDON LAYOUT

General view of the post-tensioning tendon system is given in Figure 1

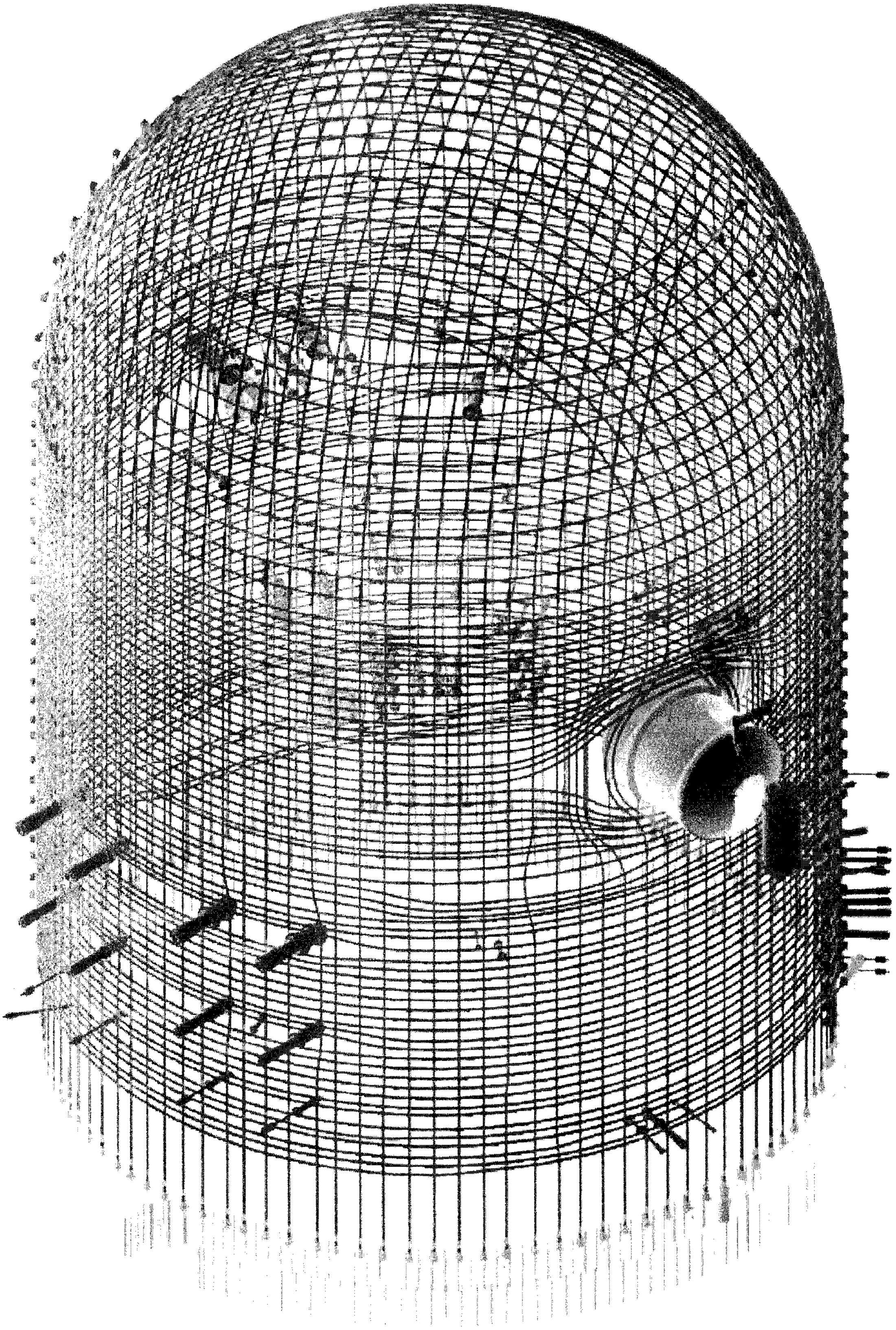

Figure 1 Plot from the plant layout model depicting the post-tensioning tendon system

SEISMIC DESIGN GROUND RESPONSE SPECTRA

The 5 % bedrock field ground spectra according to the HAF 0101(1) [5] were adopted for targets of the ground motion simulation. The horizontal ground motion spectrum was anchored to 0.2g and the vertical ground motion spectrum was anchored to 0.1g [6]. In the following Table 9 the spectral ordinates as functions of frequency are given in tabular form.

Table 9 Design ground response spectra

Horizontal spectrum						
Frequency, Hz	0.25	3.3	14.3	25	33.3	50
Horizontal acceleration, g	0.062	0.610	0.538	0.346	0.2	0.2
Vertical spectrum						
Frequency, Hz	0.25	4	14.3	25	33.3	50
Vertical acceleration, g	0.084	0.262	0.294	0.182	0.1	0.1

CONTAINMENT MODELLING DESCRIPTION

The analysis of the reactor building has been carried out using the following sequence of calculations and three main computer programs: MSC/PATRAN, MSC/NASTRAN and IVODIM.

1) The calculation models are created interactively with MSC/PATRAN version 7.6 pre-processor.
2) The basic load cases are solved for nodal displacements and element stress resultants with help of a commercial general purpose program MSC/NASTRAN version 70 [7], [8].
3) The calculation model together with its stress resultants are converted with NASDIM in-house program to make it possible to calculate the required reinforcement in the structures using in-house program IVODIM. NASDIM is a simple re-formatting program, which reads MSC/PATRAN's neutral file and MSC/NASTRAN's results files and writes them out in a format readable by IVODIM.
4) The reinforcement areas are then calculated by defining a set of load combinations of the basic load cases solved earlier by MSC/NASTRAN using in-house program IVODIM.
5) Finally the calculation results, displacements and element stress resultants from MSC/NASTRAN and required reinforcement from IVODIM, are presented graphically using MSC/PATRAN post-processor.

The Finite Element Method (FEM) [9] was utilized to solve the problems. Four- and three-noded shell elements capable to take also transverse shear forces into account were used to model the structure. Each node in the model has six degrees of freedom, a translation in the X-, Y- and Z-directions and rotations around these directions.

A 3D-model was created for the whole reactor building. The 3D-model consists of the outer containment, the inner containment, the internal structures and the base slab with the tendon gallery. The FEM-model was formed along centre lines of the concrete structures. The number of shell elements used to describe the concrete walls and floors is 22825. The columns in the internal structures were described by 48 beam elements. The properties of the elements were determined according to the concrete material properties and the nominal dimensions of the structures.

RESULTS OF THE ANALYSIS

Maximum values of displacements for the inner containment of the reactor building model are presented in Table 10. The Table 10 includes the ten basic static load cases (load numbers 1-10), four static load combinations (load numbers 11-14) and also the components of the dynamic displacements from earthquake load (load numbers 15-17).

Table 10 Maximum values of total displacements for the inner containment

Load	Basic load case or load	Displacement, mm
1	Dead load	3.4
2	Prestress after prestressing	12.2
3	Prestress after 40 years	11.2
4	Polar crane load	0.5
5	Normal conditions temperature	10.1
6	Extreme conditions temperature	33.6
7	Accident pressure	12.0
8	Pipe reactions during operation	0.1
9	Pipe break reaction	2.8
10	Pipe reactions from earthquake	0.4
11	Normal operation	14.5
12	Normal operation after 40 years	13.7
13	Design basis accident	6.7
14	Design basis accident after 40	7.4
15	Earthquake, X-displacement at top	13.6
16	Earthquake, Y-displacement at top	12.0
17	Earthquake, Z-displacement at top	1.0

The displacement time history (m) for the load case 15 are depicted in Figure 2.

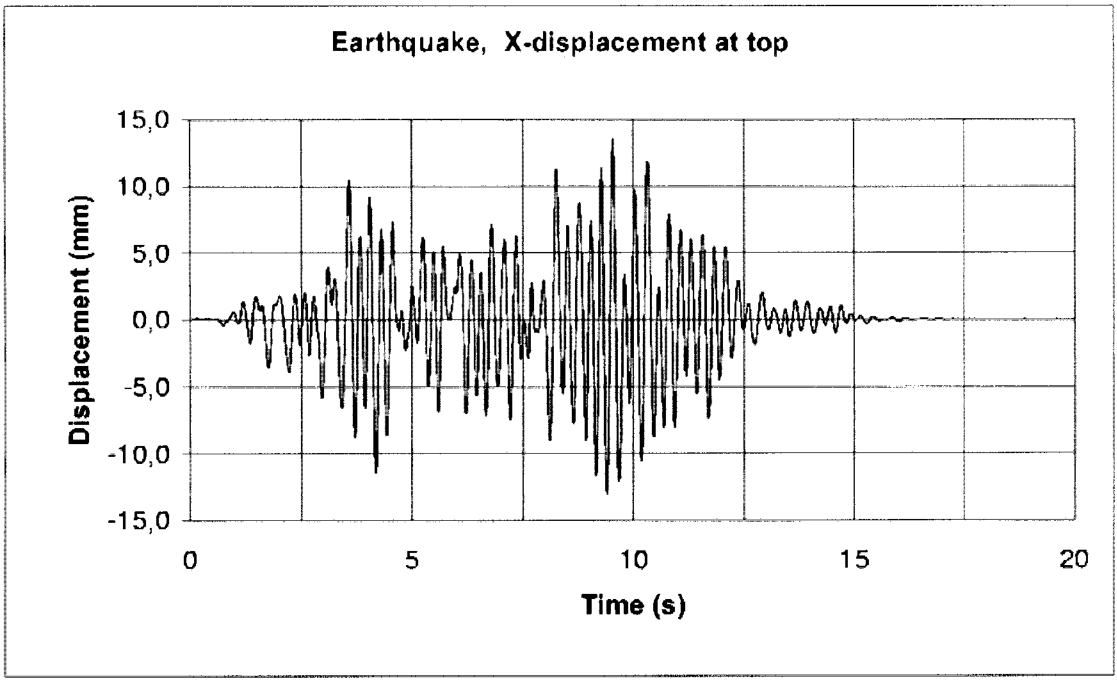

Figure 2 Displacement time history for the top of the containment for seismic load

CONCLUSION

To illustrate the differencies in structural response caused by the different modeling and analysis options the acceleration response spectra at elevation +22.5 in horizontal X-direction with 5% damping are compared. The compared models are true 3D model, component mode synthesis model and stick model. As can be seen from Figure 6 the reduced models increase the acceleration response ordinate by about the factor of two and shift the spectral peaks to higher frequencies. In this case the shift was from 5 Hz to 8 Hz. Based on above observations it can be stated that reduced models can significantly amplify the structural response and also stiffen the structure considerably.

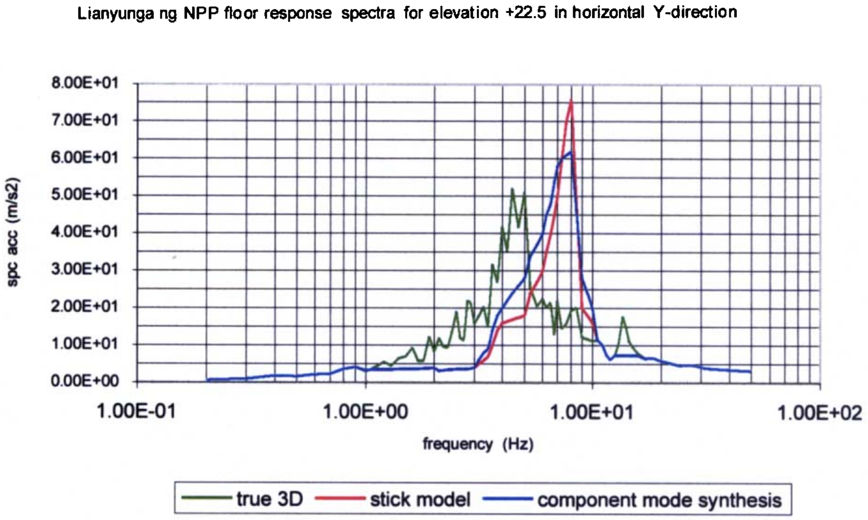

Figure 3 The comparison of structural responses calculated with different modelling assumption

REFERENCES

1. ACI 359-95 (ASME Boiler and Pressure Vessel Code, Section III, Division 2), Code for Concrete Reactor Vessels and Containments, New York, 1995.

2. SNiP 2.03.01-84. Betonnie i zchelezobetonnie konstruktsii, M., Gostroi SSSR, 1985.

3. ACI 349-97, Code Requirements for Nuclear Safety Related Concrete Structures, New York, 1997.

4. Varpasuo, P. & Whitcraft, J. S., Preliminary Design of a VVER 440 MW NPS Prestressed Concrete Containment Building, Bechtel Power Corporation, Gaithersburg, July 1985.

5. Safety Guide on Earthquakes and Associated Topics in Relation to NPP Siting, HAF0101. Approved jointly by NNSB and SSB. A Collection of Safety Guides for NPP, NNSB, Law Publisher of China, 1992.

6. Normi proektirovanija sejsmostojkih atomnih stancij. PiN AE G-5-006-87. Gosatomenergonadzor SSSR.- M., Energoatomizdat, 1989.

7. MSC/NASTRAN Linear Static Analysis. User's Guide, Version 69+, The MacNeal-Schwendler Corporation, Los Angeles, California, July 1997.

8. MSC/NASTRAN Basic Dynamic Analysis. User's Guide, Version 69, The MacNeal-Schwendler Corporation, Los Angeles, California, July 1997.

9. Zienkiewicz, O. C. & Taylor, R. L., The Finite Element Method, Vol. I and II, Fourth Edition, McGraw-Hill, London, 1989.