SEISMIC RESPONSE ANALYSIS AND IN-STRUCTURE SPECTRA FOR THE REACTOR BUILDING OF LIANYUNGANG NPP IN CHINA

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SUMMARY

The purpose of the current paper is to present the task, the methods and the results for the response analysis of Lianyungang NPP reactor building. The task is a part of the design project for the plant that is currently under progress and is jointly carried out by St. Petersburg ATOMENERGOPROEKT as head designer and IVO Power Engineering Ltd. as the consultant. For the analysis a vast 3D finite element model of the reactor building was devel-oped. The total amount of degrees of freedom in the model was 120 000 and all eigenfrequencies up to the frequency of 50 Hz were extracted from the model. The fol-lowing different parts of the reactor building complex were included in the model: 1) foundation soil; 2) joint base slab for all reactor building structures; 3) internal structures inside the inner containment; 4) primary cooling circuit pipelines and equipment items of the reactor cooling system; 5) inner containment; 6) outer con-tainment. The load was the three component seismic excitation time history set that was fitted with ground response spectra anchored to 0.2g and specified in chinese seismic code for nuclear power plants. The results of the analysis were the stresses in the structures and the in-structure response spectra for the floor elevations of the re-actor building As a conclusion of the work done following remarks can be made: 1) the analysis was a vast calculation effort for example the mode extraction run consumed 48 CPU hours on SGI Octane R10000 work station; 2) the results obtained from the full 3D model deviated significantly from the response results obtained by super element or component mode synthesis reduction of the calculation set; 3) the obtained response spectra differed also significantly to lower side from the obtained by the use of sim-ple stick model developed for the preliminary analysis.

INTRODUCTION

The purpose of current investigation is to demonstrate that all devices, numerical or modelling, used to decrease the size of the model used in response spectra generation tend to increase increase the structural response. The reference response of the reactor building to be investgated was developed by the use of a stick model that included only a couple tens of degrees of freedom. As the desig and analysis progressed the 3D model of the reactor building was developed using four node shell elements. However, the number of the degrees of freedom in the model were reduced by superelement usage to make analysis task more tractable with respect to computer time and space. The superelement model was subsequently improved by the use component mode synthesis method. The problem with all these methods was that the structural response was unreasonably for some types of seismic excitations. As the last resort the true 3D model of the building was analysed for seismic excitation without any reductions in the size of model. The results were surprising as will be explained in subsequent sections.

DESCRIPTION OF THE STRUCTURE

The reactor building consists of the outer containment, the inner containment, the internal structures and the base slab with the tendon gallery. 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 inner

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containment is a prestressed concrete shell structure that consists of a cylindrical part and a hemi-spherical dome. The inner surface of the containment is covered with a 6 mm thick carbon steel plate to secure the tightness. The inside diameter of the cylinder is 44.0 m. The height of the cylinder part is 41.2 m and the top of the dome is at level +71.60. The thickness of the cylinder and dome are 1.2 m and 1.0 m respectively. The prestressing of the inner containment will be performed by means of the post-tensioning system. The tendons are divided into two horizontal and two vertical sets. The horizontal tendons in the cylinder and dome will be going around the whole 360 degrees so, that the anchorage is in turn on the opposite sides of the containment. The vertical tendons are inverted U-shaped tendons and they are divided into two groups of tendons at 90 degrees to each other. The base slab is utilized for the anchorage of the vertical tendons. 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 100 mm from the cylinder wall of the internal 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. The lay-out section of the reactor building is depicted in Figure 1.

CHARACTERISTICS OF THE MATERIALS

The grade of concrete for the design of the reactor building is B25 according to Russian concrete classification given in building code[SNiP, 1985], except in the inner containment where the grade of concrete is B45. A-III hot rolled ribbed bars according to Russian code [SNiP, 1985] were considered for principal reinforcement. Prestressing tendons are strand 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 mm2 and nominal mass per metre is 65 kg/m. Modulus of elasticity is 199000 MN/m2 and coefficient of thermal expansion is 1.0·10-5 /°C. The soil is weak-weathered metamorphic rock. The strength and elastic characteristics for the soil are as follows:

- static elasticity modulus — Eo = 37300 MPa,
- dynamic elasticity modulus — E = 45500 MPa,
- weight density — ρ = 26.4 kN/m^3,
- speed of longitudinal waves — Vp = 4640 m/s,
- Poisson's ratio — ν = 0.24,
- shear modulus — G = 14800 MPa.

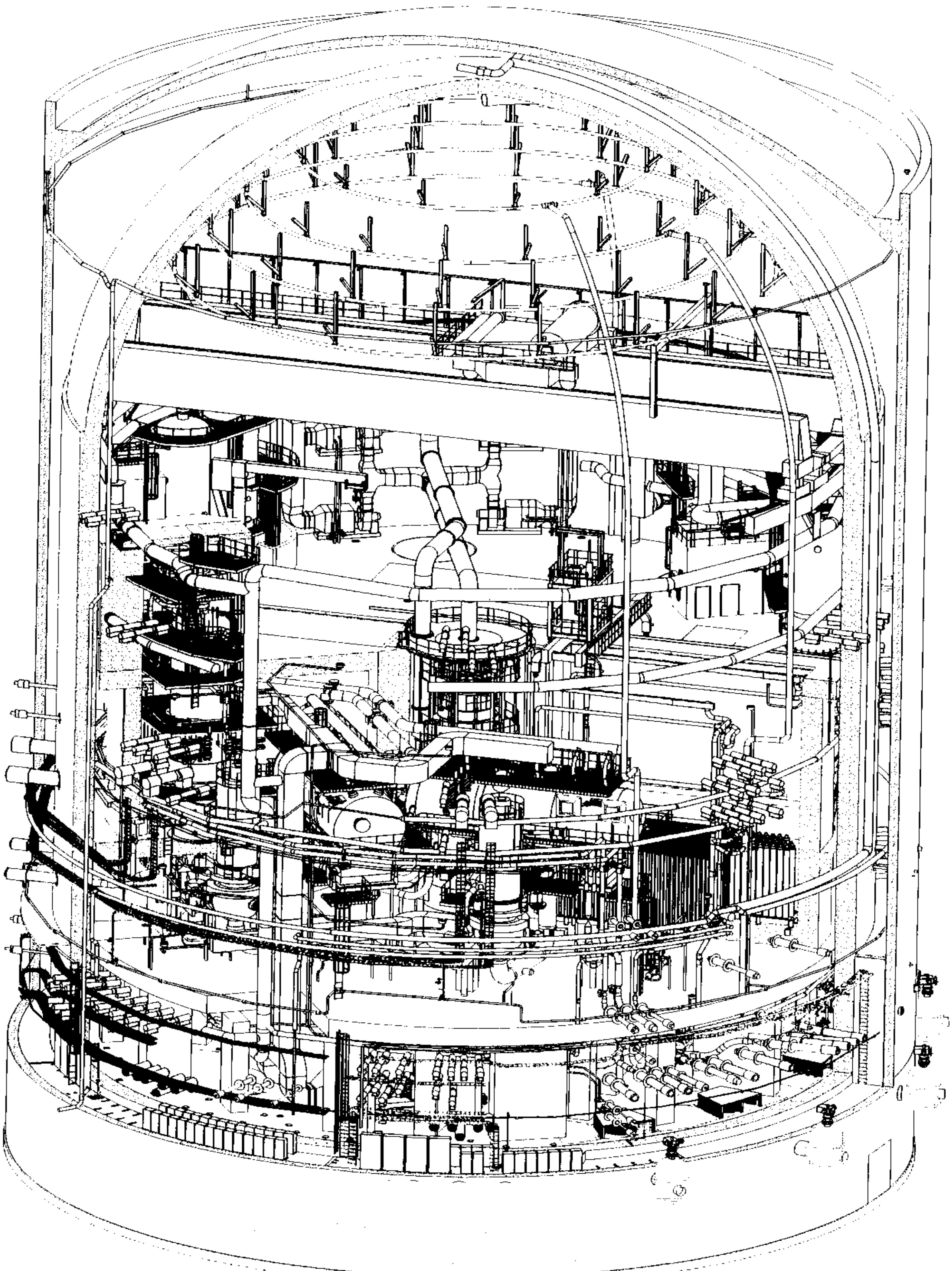


Figure 1. The lay-out section of the Lianyungang NPP reactor building

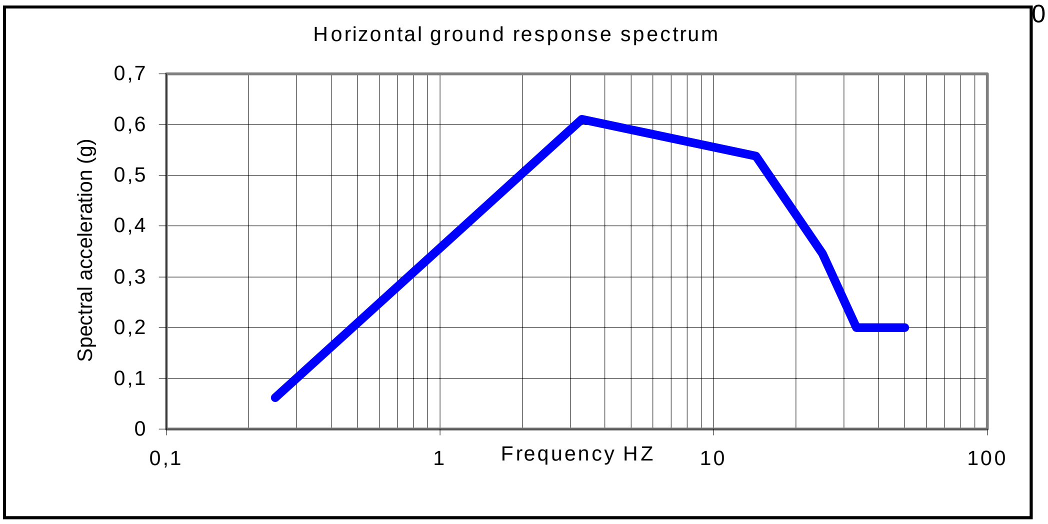
DEFINITION OF EARHQUAKE EXCITATION

Chinese seismic code HAF 0101(1) [HAF 0101(1), 1992] was adopted as the basis for ground motion definition. Target spectra for ground motion simulation were the ground spectra for bedrock having 5 % damping ratio. The horizontal ground motion spectrum was anchored to 0.2g and the vertical ground motion spectrum was anchored to 0.1g. In the following table the spectral ordinates as functions of frequency are given in tabular form.

Table 1 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

In graphical form the horizontal target spectrum for the ground motion to be simulated is depicted as follows:



0,25 0,062

Figure 2 Horizontal design spectrum according to HAF 0101(1)

The time histories to be generated shall fit to the target spectra defined above and this fit is defined with the following characteristics:

- The mean of the zero-period acceleration (ZPA) values (calculated from the individual time histories) shall equal or exceed the design ground acceleration.

- In the frequency range 0.5 to 33 Hz, the average of the ratios of the mean spectrum (calculated from the individual time history spectra) to the design spectrum, where the ratios are calculated frequency by frequency, shall be equal to or greater than 1.

- No one point of the mean spectrum (from the time histories) shall be more than 10 % below the design spectrum. When responses from the three components of motion are calculated 3) No one point of the mean spectrum (from the time histories) shall be more than 10 % below the design spectrum. When responses from the three components of motion are calculated.

DESCRIPTION OF THE FINITE ELEMENT ANALYSIS MODEL

Four-noded quadrilateral shell elements capable to take also transverse shear forces into account were used to to develop the finite element 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 true 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 model was formed along centre lines of the concrete structures. The number of shell elements used to describe the concrete walls and floors is 21994. 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. The main components were described by point mass elements. In this way, the weight of these components was taken into account both in static and dynamic analyses. Water in the pools of the internal structures was also modelled by point mass elements.The prestressing tendons in the inner containment were described by 16072 bar elements. The tendons were placed in their real places giving offsets for the bar elements. The vertical tendons are placed on the centre line in the cylinder. In the dome the vertical tendon group 1 is placed a little outside of the centre line and the group 2 a little inside of the centre line. The horizontal hoop tendons are offset 0.36 m outside of the centre line in the cylinder and 0.30 m outside of the centre line in the dome. In the vicinity of the equipment hatch opening every second hoop tendon is bended 0.5...0.8 m inner. The equivalent change of temperature was used represent the prestressing forces of the tendons. The change of temperature of the bar elements varies from -364.3 to -716.7 °C, which correspond stresses from 725 to 1426 MN/m^2. The boundary conditions for the 3D-model were described by spring elements in static analysis and by spring and damper elements in dynamic analysis. All the nodes against the rock were connected to springs (and dampers) and the other end of the spring and damper elements were connected to one nodal point representing ground and situated below the building. The ground accelerations were input to that node in the seismic analyses, but in other analysis that node was fixed in all six directions. The spring and damping constants were calculated so that they represent the properties of the bedrock modeled as an elastic half space. The following right handed global coordinate system was used in this study. The origin of the model is in the centre point of the reactor building at the level +0.00. The X- and Y-axes are in the horizontal plane and the Z-axis is vertical. The X-axis is to the direction of the refuelling pool, which is in the direction 0 degrees in the drawings. The Y-axis is normal to the X-axis according to the right hand rule so that the Z-axis points upwards. The plot of the finite element model is depicted in Figure 3.

SEISMIC RESPONSE ANALYSIS

According to the USNRC Regulatory Guide 1.29 [USNRC, 1978] the reactor building belongs to the first category and thus the structural response earthquake load must be assumed elastic and the building must be analysed as elastic. To predict the seismic response of structures subjected to the design earthquakes, the calculation model presented in Section 5 was used. Soil-structure interaction was taken into account by coupling the structural model with the foundation medium. The earthquake excitation was applied to a big mass because the large mass method was used to get the desired time history. The big mass was connected by springs and dampers to the base level of the structure. The eigenvalues and eigenmodes were calculated by the Lanczos method. All modes below 50 Hz were used in the modal transient analysis to solve the displacement, velocity and acceleration histories. Damping of structures was determined by the equivalent viscous damping and the damping value was 5 % for all modes. Solution time-span was selected to be 20 seconds with an increment of 5 ms between each calculation point. Duration of the design earthquake was 15 seconds. The acceleration response spectra were calculated using four different damping values, 0.5, 2, 5 and 10 % of critical damping, at the following 73 frequencies: 0.2, 0.3, 0.4, ... , 3.0, 3.15, 3.3, 3.45, 3.6, 3.8, 4.0, 4.2, 4.4, 4.7, 5.0, 5.3, 5.661, 6.0, 6.25, 6.5, 6.75, 7.0, 7.3, 7.6, 8.0, 8.5, 9.0, ... , 13.0, 13.565, 14.0, 14.5, 15.0, 15.801, 17.0, 18.5, 20, 24, 27.238, 31.127, 33, 40 and 50 Hz. The response spectra were determined at points near the centre of the concrete floors of the internal structures and base slab and at two extra points both in the inner and outer containment. At each point, the spectra were evaluated in the global X-, Y- and Z-directions.

RESULTS OF RESPONSE ANALYSIS

The results of the response spectra calculations for the elevation of +22.5 are presented in Figures 4 and 5. The horizontal argument axis in the response spectra plots gives the frequency in Hz in logarithmic scale. The minimum value is 0.1 Hz and the maximum value is 100 Hz. The vertical ordinate axis gives the spectral accelerations in meters per square seconds in linear scale. The minimum value for all plots is 0.1 m/s^2 and the maximum value varies according to the global co-ordinate direction. All response spectrum plots give spectra for four damping ratios, namely, 0.5%, 2%, 5% and 10%. In the discussion of following section the 5% response calculated with different modeling approaches are compared.

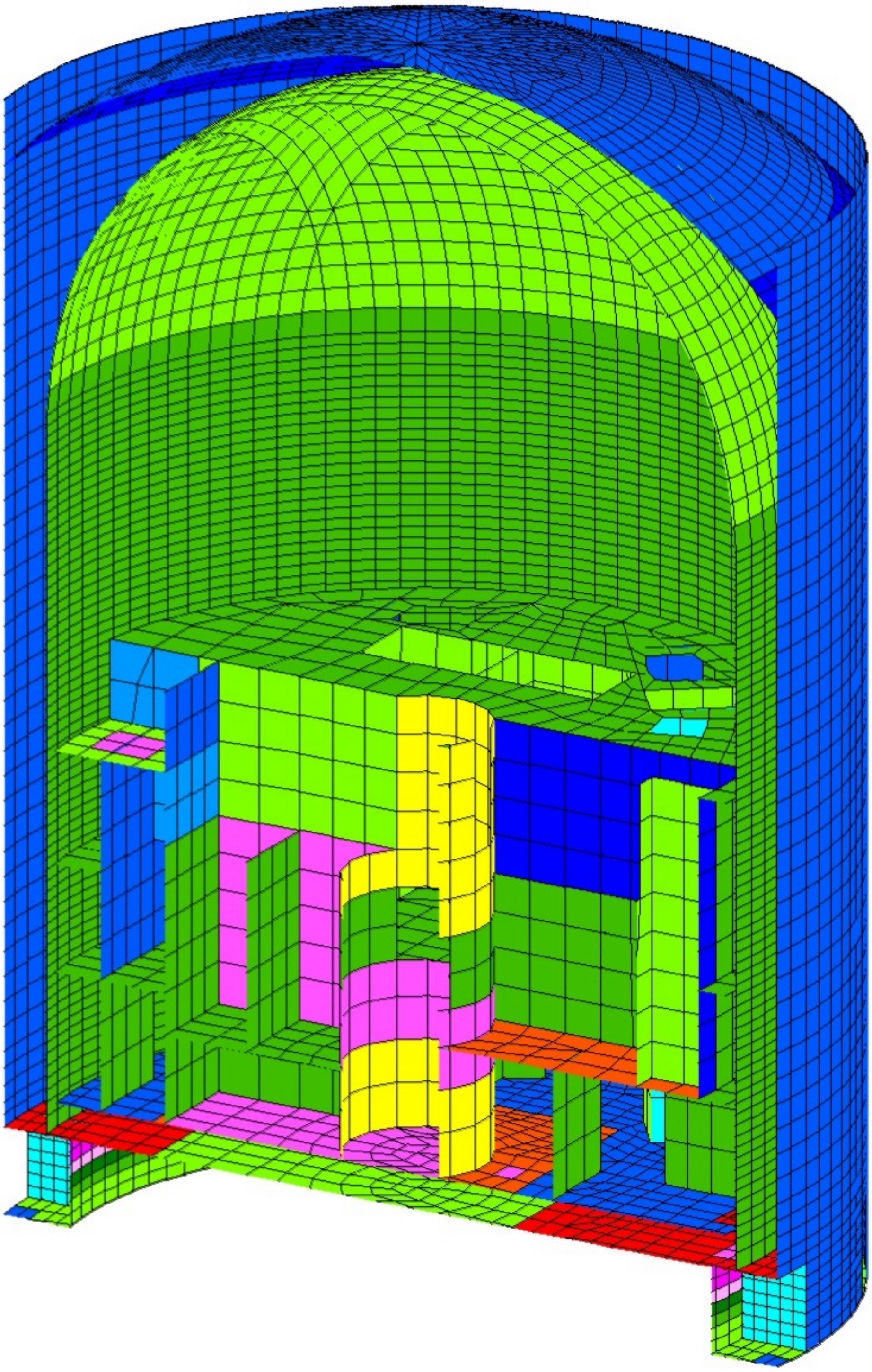


Figure 3 The geometry of the finite element model of the reactor building

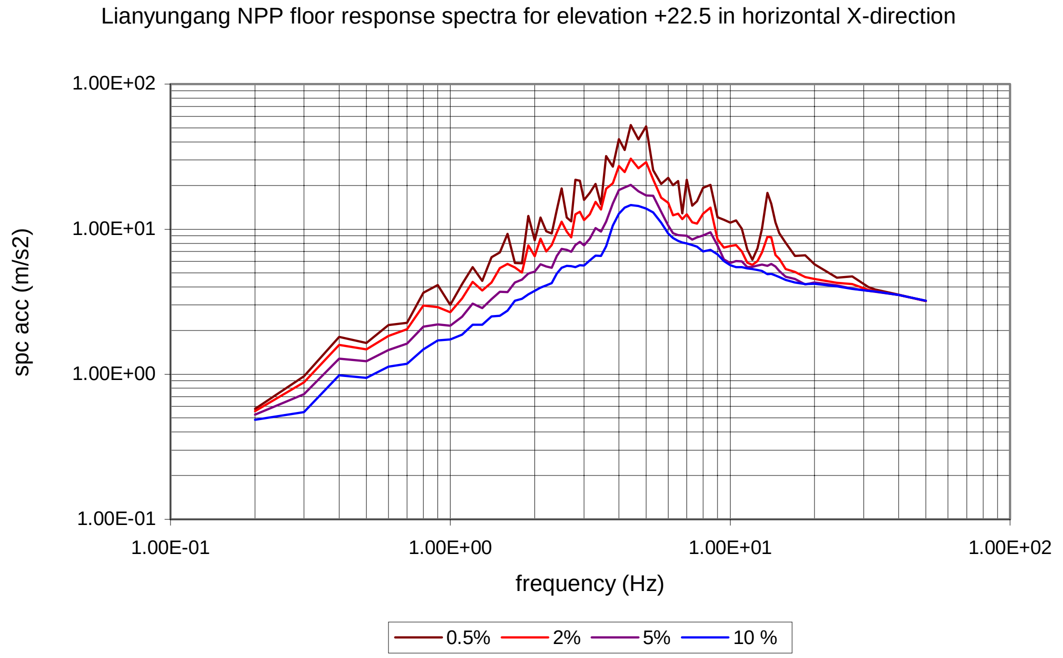


Figure 4 Acceleration response spectra of elevation +22.5 in global X-direction

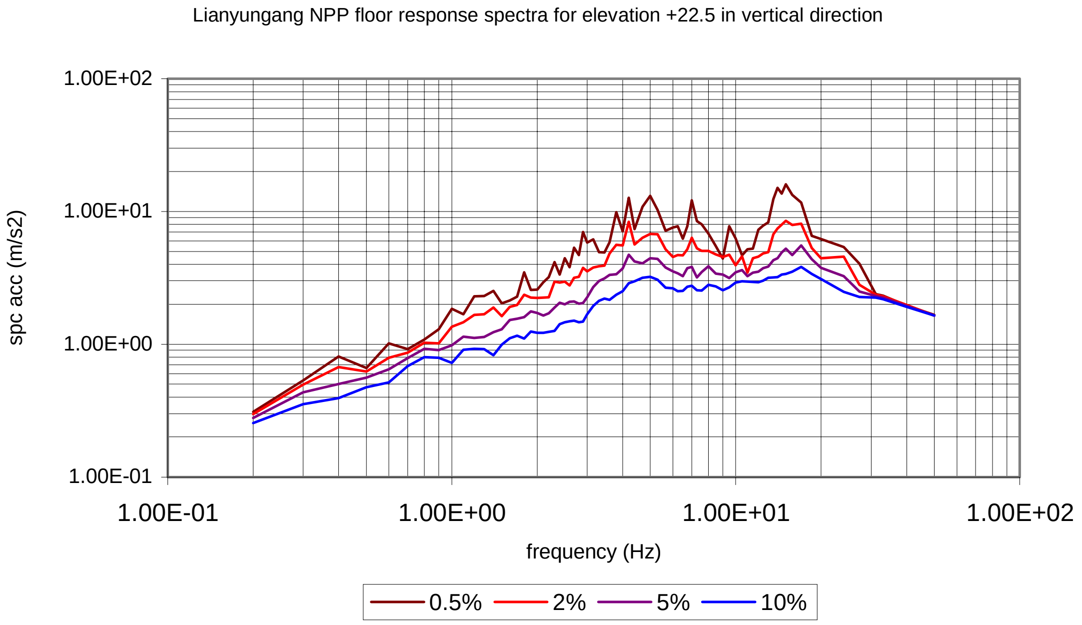


Figure 5 Acceleration response spectra of elevation +22.5 in vertical direction

CONCLUSION

To illustrate the differencies in structural response caused by the different modelling 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.

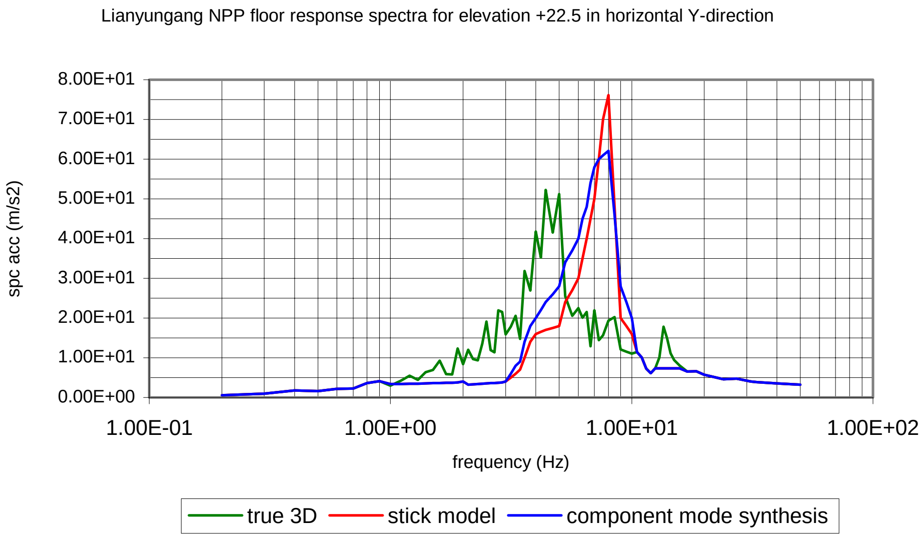


Figure 6 The comparison of structural responses calculated with different modelling assumption

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