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Response of a WWER-440 MW main building complex to blast input motion

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ABSTRACT: The paper presents a blind prediction of Paks NPP WWER-440MW Main Building response to blast input motion. A twin units structural model was developed, assuming surface founded structures supported on nine separate foundations. Multiple foundation coupled impedances were generated. Fixed base and pseudo-static modes of the twin units model were extracted. A blast response SSI analysis was carried for generation of the time histories and spectra at the response recording locations. The observations and conclusions are drawn as result from the spectra comparisons.

1. INTRODUCTION

The work presented in this paper is performed under an IAEA contract within its CRP "Benchmark Study for Seismic Analysis and Testing of WWER-type NPP". EQE-Bulgaria, supported by EQE-International, performed a SSI structural response analysis of Main Building of Paks NPP, Hungary, for blast input motion using multiple foundations support excitation code. The explosion full scale tests were carried out by ISMES for determining the dynamic behavior of the structure. The blast input motion records were distributed among participants of the study for blind prediction of the structural response and for assessment of the SSI effects in the modeling and dynamic response analysis procedures.

1.1 Description of the Main Reactor Building Complex

The plant has four identical units with WWER-440MW/213 reactors, which are grouped in two pairs of units arranged as mirror images. The twin units Main Building consists of embedded Confinements with a gap between them, resting on a common base mat, two Condensing Towers resting also on the same base mat, Reactor Hall Upper Structures for both units, surrounded by Transverse and Longitudinal Galleries, and Turbine Halls, resting on separate foundations. The transverse cross-section of the reactor unit is shown on Fig.1.

The base mat is founded at El.-8.67m. It is about 2m thick, 149m long and 81m wide. The Confinement is a complex box type cast in-situ structure with a few floors and many walls with different thicknesses varying from 0.5 to 1.5m. A concrete topping with different thicknesses resides on the floor slabs. The operation deck mat is on El.18.90m. The Condensing Towers rise up to El.49.65m with 5 floor slabs and an intermediate wall; the walls 1.5m thick are designed to withstand 0.25MPa internal pressure. The Reactor Hall rests on the Confinement at El.18.90m and spans over two bays of 39m and 12m. The steel structure is composed by pin footing columns and two bay trusses, supported by intermediate columns and covered with precast concrete panels. Two cranes operate in the larger bay and one crane in the smaller bay. The outer walls are composed of precast concrete cladding panels. The Reactor Hall roof is at El.51.00m.

The Longitudinal Gallery is attached on the eastern side to the Reactor Building and spans 12m to the Turbine Hall. The Gallery supporting elements are concrete pin connected girders and precast panels with topping. The Transverse Galleries are attached at North and South side of the Reactor Buildings. They are supported by frame structures, composed by concrete columns and pin connected 12m long girders. The Galleries strip foundations are separated from the common base mat. The roofs of Transverse and Longitudinal Galleries are at different elevations. Staircases with 25cm thick concrete walls are arranged at the Galleries intersection corners. The Turbine Hall is constructed by steel columns and trusses with separate strip foundations, arranged in such manner that on the construction joint line between the units strips are continuous. The cladding panels are attached to the columns through cantilevers 60cm long so that their shear stiffness cannot be transferred to the columns in longitudinal direction. At the Turbine Hall roof in longitudinal direction there is an opening where the so-called Deflector is arranged. This structure reduces the roof diaphragm stiffness. The turbines rest on separate foundations and do not effect the Turbine Hall structure. In the Turbine Halls there are three cranes supported by the steel columns corbels at El.19.27m.

1.2 Description of the Analyses Steps

A substructure method of SSI analysis has been applied to assess the blast response of the Main Building using the CLASSI chain of programs [1]. The substructure approach separates the SSI problem into series of simpler problems, solves each independently, and superposes the results. Several assumptions apply to the analysis procedure. Most notably, the foundations are assumed to be surface founded and to behave rigidly. Full bonding is assumed between the foundation and the soil. As the blast excitation with small explosions cannot induce large soil strains, the non-linear soil properties were not developed. The foundation system of the Main Building is comprised of nine separate foundations and multiple foundation coupled impedances were generated. Additionally pseudo-static modes for the twin units model were needed for analyses of the multiple foundations support structure. In-structure response spectra were generated at the blast response measurement locations and at the foundations reference points using the acceleration response time histories.

2. DEVELOPMENT OF THE REACTOR BUILDING MODEL

A 3-D coupled model of Main Building was developed. It is composed of two separate models: a stick model of Confinement and Condensing Tower, and a finite element model of the Reactor Hall, Turbine Hall and Galleries. The twin units model arrangement has been made by using the symmetry along axis 12. Two coupled models with opposite X-coordinates have been connected through the common base mat and strip foundations at the construction joint. The fixed-base dynamic characteristics of all models have been extracted. The characteristics of the twin units model were projected to the Foundation Reference Points (FRP) on the common base mat and strip foundations, at which the foundations motions were determined.

2.1 Stick Model of Reactor Confinement and Condensing Tower

The *WALLY* program [2] has been run for stick model development. It calculates the overall stiffness and mass parameters for structures comprised of shear walls and floor slabs by combining the contributions of individual elements. The base mat geometry was included in the *WALLY* run by its mass density including the concrete, the equipment and the tributary wall masses. As the fixed-base model was investigated, the foundation mass and the mass moments of inertia were included as foundation mass matrix in the soil-structure model. Miscellaneous equipment items like cabinets, piping, cable trays, were accounted for by increasing the slabs mass densities. The large equipment items such as tanks, heat exchangers, and pumps as well as the primary loop components and the spent fuel pond have been included with their masses and geometrical locations. Finally, a stick model was constructed using lumped mass nodal points and beam elements. A separate stick has been developed for Condensing Tower. The total mass of the stick model is about 190 000t including base mat mass of 40 800t. The material properties of the concrete in the model are: E=33 000MPa; ν=0.20; ρ=2.5t/m^3. The stick model is shown on Fig.2; its fixed-base eigen frequencies are presented in Table 1.

2.2 Model of Upper Structure of Reactor Hall, Turbine Hall and Galleries

A 3-D finite element model of the Reactor Hall, the Turbine Hall and the Galleries has been created by incorporating the simplified 2-D models with equivalent stiffnesses developed from the analyses of detailed 2-D models of each sub-structure for unit static loads. Using this approach a significant reduction of the global 3-D model size for SSI analyses was obtained.

The main assumptions of the model creation are next described. The columns are spaced out by other one and their stiffnesses are concentrated in accordance with the strip foundations arrangement. The longitudinal beams cross-sections were kept unchanged. The crane beams were also included in the model. The equivalent bracings span 12m instead of 6m and some reduction of their cross-sections was needed to achieve the designed frame stiffnesses. The cladding panels were excluded from the model due to the large flexibility of the steel cantilevers, to which they are attached. The roof composed of trusses and precast panels is relatively rigid for loads in its plane, but will not behave like a rigid deck due to the Deflector openings. An equivalent roof diaphragm model has been developed by beam and shell elements to achieve the equal displacements between the detailed roof model and simplified model in the displacement control locations. The Galleries' floor slabs are modeled with beam and shell elements with equivalent geometric properties and thicknesses respectively. The shell elements equivalent thicknesses are assessed by the stiffnesses of the floor panels and concrete topping. The precast cladding panels at the Transverse Galleries are directly attached to the reinforced columns by weldings between columns and embedded steel plates in the panels and they are modeled as shell elements. The Staircases walls are also modeled by shell elements.

The cladding panels masses are lumped in the corresponding model nodes. The masses of the columns, bracings, longitudinal and crane beams are distributed along the corresponding beam elements. The floor and roof slabs masses and the masses of the supporting girders and trusses are distributed over the corresponding shell and beam elements. In the roof shells masses is included 25% of the snow weight. The total mass of the 3-D model is about 43 000t. The material properties of the concrete used in the model are: E=30 000MPa; ν=0.20; ρ=2.4t/m^3. The material properties of the steel are: E=206 000MPa; ν=0.30; ρ=7.85 t/m^3.

All four units are serviced by three cranes in Turbine Hall. It is assumed that two of them are parked according to the requirements at axes 1 and 22. Two heavy cranes between rows C and D are installed in the Reactor Halls of the twin units as well as two light cranes below them. Another two light cranes are installed between rows D and E in the Reactor Halls. It is assumed that the cranes are located in their parking places at axes 6 and 18 for Units 1 and 2 respectively. All cranes are modeled in a simplified manner as masses and stiffnesses.

2.3 Coupled Model

The coupled model on Fig.3 has been composed of the generated stick model and the 3-D finite element model by some additional rigid links between them. Supporting nodes of the coupled model are located at the base mat and the strip foundations FRP points. The model includes 522 nodes, 318 shell and 838 beam elements, and it has 2940 DOF. The total mass of the coupled model is 233 000t including masses of the base mat and the strip foundations.

The coupled model was initially studied with *SAP90* program and after that it was transferred for analysis with the *MODSAP* program [3]. Good overlap of the dynamic characteristics of the coupled model have been achieved by both analyses. Two eigen frequency extraction analyses have been carried out for the coupled model. Initially the model has been analyzed as fixed-base model. More than 250 frequencies were required to reach cut off frequency of 30Hz due to the complicated building structural system. After that for comparison and control purposes the model has been analyzed with spring supports. The values of the soil springs have been developed using subgrade reaction concept. The eigen frequencies and modal mass participation coefficients for springs supported model are presented in Table 2.

2.4 Twin Units Model

The Main Building is a complicated twin units structure and its blast response study should assess the mutual influence of the structures as well as the structure-to-structure through soil interaction. The twin units model has been developed utilizing the capabilities of *SSIF* program [4]. It requires preparation of separate fixed-base models for each of the Main Building units, which are assembled with the foundation system model, having corresponding coupled impedance functions. The development of the twin units model was done by creation of symmetric about vertical plane model to the coupled model. It was also analyzed for extracting fixed-base eigen frequencies and mode shapes. A good overlap of frequencies and modal mass participation coefficients of the both models has been reached.

One additional preparatory analysis, so-called pseudo-static modes analysis, is required for SSI response analysis of multiple foundation support structure. It is a classic static analysis of a structure with multiple supports, which consequently is loaded by a set of unit displacement and rotation support motions at each support node. The corresponding deformed shapes of the model are the pseudo-static modes. The *MODSAP* program has been used in this analysis to obtain common format of the output data by the pseudo-static and mode shapes analyses.

For the SSI analyses of the Main Building, the concrete material damping was taken 4% from RG 1.61 [5] due to the fact that the blast input motion was low energy motion, which could not produce non-linear response. According to the RG 1.61 the steel material damping in this case should be 2%. Having this in mind, three cases of modal structural damping have been studied varying it with 25%. In this paper, only the 4% damping results are presented.

3. DEVELOPMENT OF SSI PARAMETERS

The Paks NPP Main Building is founded on a layered, relatively soft soil and it is embedded about 8.7m below grade. The soil data for the site has been prescribed by IAEA. The low strain soil profile properties were assumed as best estimate values. The soil layers were modeled up to 100.50 m below the grade, neglecting the backfill layer, and an elastic half space was assumed below the soil profile model. The soil property degradation curves were not required for this study due to the low energy of blast excitation. The material damping of 1% was chosen, which is negligible compared with the radiation damping. In the SSI blast response analyses the soil properties were varied with 50% and 200%.

Using the low strain soil properties the SSI parameters for the rigid massless foundations were calculated. The SSI parameters here refer to the foundation input motion and foundation impedance functions. The impedance and scattering functions were calculated only for the best estimated soil properties. For other soil cases they were obtained by scaling factors pointed above.

3.1 Foundation Model of Main Building Complex

The foundation system of the Main Building consists of a base foundation mat, supporting the Confinements and Condensing Towers of the twin units, six regular strip foundations under the columns of the Turbine Hall and two irregular strip-like foundations under the columns of the Transverse Galleries. It was accepted to model the base foundation mat with larger elements and the strip foundations with smaller elements in compliance with their real geometrical sizes. Fig.4 shows the layout of the foundation system model, composed by 9 foundations and 364 subregion elements. The FRP points are marked with crossing on the layout. All impedance and scattering functions were calculated for the corresponding FRPs.

3.2 Development of Impedance and Scattering Functions

Only the surface founded structural model has been investigated neglecting the embedment effects. Because of the relatively soft backfill material the embedment would only cause slightly higher soil springs. Damping will be effected much more but neglecting its influence a little bit higher values of the structural responses will occur. The calculation of impedances and scattering functions for the foundation system model has been carried out assuming that it rests on the top of the second layer of soil profile. This assumption is reasonable having in mind that the second layer top is at El.-9.5m while the base mat bottom is at El.-8.67m.

The impedance functions were calculated by the programs *GLAY* and *CLAN* [6]. For surface foundations and vertically propagating incident SH-waves the foundation input motion is equal to the free-field motion. The exact foundations geometry was modeled in *CLAN* using the symmetry, Fig.4. 24 frequencies, covering the frequency domain of interest (0.1-30.0Hz), were used in *GLAY* for calculation of Green's function.

For each foundation was generated a set of impedance functions forming the foundation impedance matrix. The foundation impedance matrixes for all 9 foundations form the foundation system impedance matrix, in which foundations coupling impedance matrixes are included too. The most important are the coupling matrixes between base mat foundation and adjacent strip foundations, which express the foundation-to-foundation through soil interaction. For the model of the twin units this influence is not negligible.

4. FREE FIELD BLAST MOTION AND SSI BLAST RESPONSE ANALYSIS

The full scale dynamic testing of the Paks NPP was conducted by ISMES in December 1994. The blasts location was about 2.5 km from the Main Building. Three different blast excitations were performed: a preliminary single blast test for calibration of the recording equipment and two main blasts with a time delayed multiple charges excitation. The nearest to the Main Building free field registration station was at a 119 m distance aside of the reactor. The blast motions recorded in this station were used as input time histories.

Two sets of free field time histories from the first main blast were supplied by ISMES. The first set consists of three velocity time histories. The second set consists of three acceleration time histories derived by the first set. The time duration of the presented records is 30 sec with time step of 0.005 sec. The plots of the acceleration time histories and the corresponding response spectra are presented on Fig.5 and Fig.6. The predominant blast input motion frequency of 15Hz can be recognized. During the blast excitations the structural response time histories were simultaneously recorded. Locations of the instrumentation transducers have been provided to the participants for a blind prediction of the structural response.

The program *SSIF* [4] has been applied to perform SSI blast response analyses of Main Building. It uses the foundation impedance and incident wave scattering functions, and the pseudo-static and mode shapes of the structure, in combination with free field acceleration time histories to define the problem. Definition of *SSIF* analysis problem requires also foundation mass matrixes, data for variation of soil and structure properties, as well as in-structure response locations. In the SSI blast response analyses the 3-component acceleration time histories were generated at 23 locations totally. The output acceleration time histories were truncated to 25 sec because of the long decaying part of the response motions. The time histories obtained at the center of masses nodes of the twin units models were transferred by the rigid body motion principles to the corresponding measuring points. A full set of acceleration response time histories at points of blind prediction was plotted and supplied to ISMES for evaluation and benchmarking against the results of other participants.

5. BLAST RESPONSE PARAMETERS REVIEW AND CONCLUSIONS

Blast response spectra were generated from the acceleration response time histories using 2% damping. Some of the generated response spectra are presented on Figures 7 to 10.

Fig.7 presents a comparison of the foundation input motions of the symmetric strip foundations along row B. A very good overlap of the spectra can be seen at all three directions. The response spectra of the free field motion are also plotted on Fig.7 and it appears to be lower than the corresponding foundation motions spectra in transverse and vertical direction This is due to the influence of the motions of the adjacent massif base mat on the motions of the relatively light strip foundation and to the fact that the strip foundation is small and instead to attenuate it amplifies the blast input.

More detailed observations can be made by comparing the response spectra of the base mat motions and the free field input motion, overplotted on Fig.8. The base mat excitation is significantly reduced in comparison with the free field motion over the whole frequency range of interest. These results approve the soil-structure interaction activation even at low energy blast excitations. The thick and massif base mat is very rigid and rests on relatively soft soil layers so the SSI effects like reduction of the foundation input motion is logically to be obtained.

The response spectra at the tops of the Condensing Towers are plotted on Fig.9. A very good overlap of the response spectra is noticed. The base mat input motions are also shown in the figure. Comparing the response spectra the amplification of base mat motion through the Condensing Tower can be assessed. The amplification factors are very high in longitudinal and vertical direction for responses at the predominant excitation frequency (15 Hz). This means that the foundation rocking components induce the significant amplification to the response parameters, due to the height and rigidity of the Condensing Towers.

Fig.10 shows the response spectra at the heavy crane level at Reactor Hall and the spectra of the operation deck and base mat motions. The amplification of the motions through the rigid Confinement is less than the amplification through the flexible Reactor Hall structure. Some shift of the highest response frequency in the transverse direction can be also pointed out.

Conclusions

The created twin units model allowed efficiently to generate acceleration time histories in the blind prediction locations. The presented blast SSI response analyses of the Paks NPP Main Building approved the sensitivity of the structure to dynamic excitations. Even in low energy excitations the SSI effects can be recognized. Reduction of the base mat motion in comparison with the free field motion cannot compensate the high amplification in the structure response due to its irregularity. The influence of foundation-to-foundation through soil interaction is not negligible and should be considered for multiple foundation supports structures.

REFERENCES

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3. Computer Program *MODSAP*. 1994. PC Version 1.2P
4. Computer Program *SSIF*. 1996. PC Version 1.3x
5. RG 1.61.1973. *Damping Values for Seismic Design of Nuclear Power Plants*. US AEC.
6. Computer Programs *GLAY & CLAN*. 1993. PC Version 1.3P

TABLE 1

Fixed-base Stick Model Eigen Frequencies

MODE	FREQ[Hz]	X-DIR	Y-DIR	Z-DIR
1	5.42	0.915	33.593	0.048
2	6.12	45.598	1.651	0.168
3	8.37	22.076	1.896	0.002
4	10.48	0.119	45.941	0.011
5	11.52	16.623	0.450	2.230
6	12.60	1.056	1.354	7.565
7	13.68	4.242	1.825	5.724
8	15.98	0.833	0.063	0.057
9	17.18	0.060	0.065	2.956
10	17.45	0.000	3.587	0.026
11	18.94	0.139	0.777	3.426
12	20.42	0.170	0.918	55.361

TABLE 2

Spring Supported Coupled Model Eigen Fr.

MODE	FREQ[Hz]	X-DIR	Y-DIR	Z-DIR
1	1.37	26.332	39.418	0.029
2	1.44	26.366	3.419	0.000
3	1.48	32.092	14.281	0.004
4	1.78	0.221	27.341	0.058
5	2.00	2.127	0.441	0.071
6	2.29	1.162	0.315	0.033
7	2.50	0.049	0.453	81.118
8	2.64	0.427	0.133	3.155
9	2.76	0.095	0.353	0.134
10	2.77	0.221	0.937	0.087
11	2.79	0.130	0.622	0.000
12	2.83	0.695	6.675	2.357

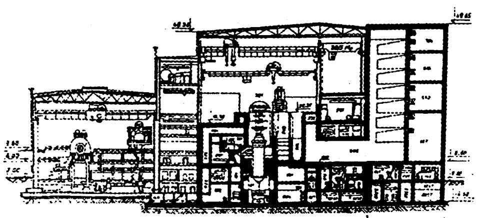


Fig.1 Transverse Cross-Section of Reactor Unit

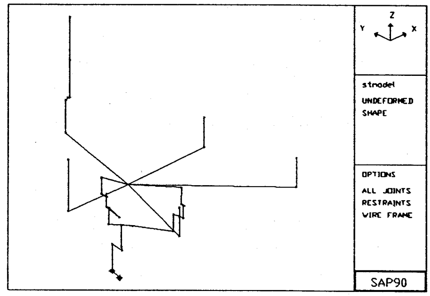


Fig.2 Stick Model

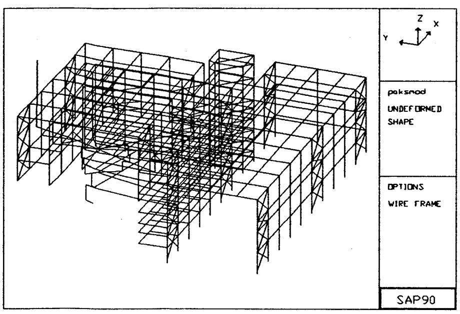


Fig.3 Coupled Model of Main Building

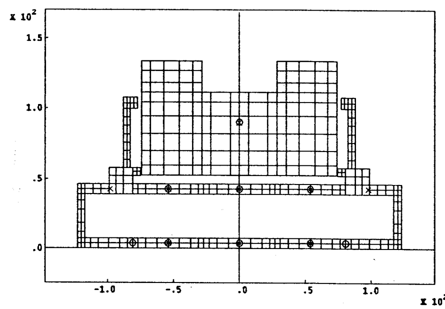


Fig.4 Foundation System Model

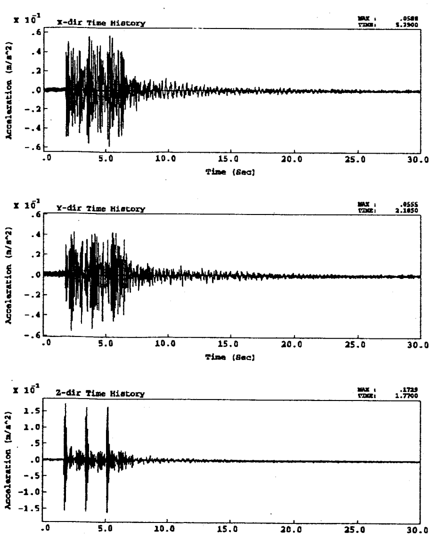


Fig.5 Blast Free Field Acceleration Motions

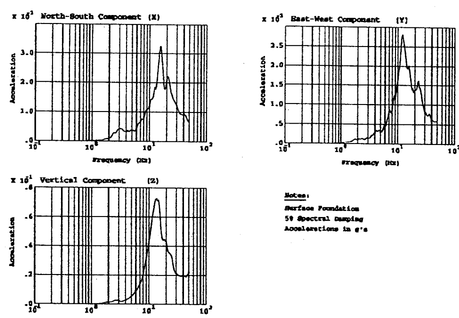


Fig.6 Blast Free Field Response Spectra

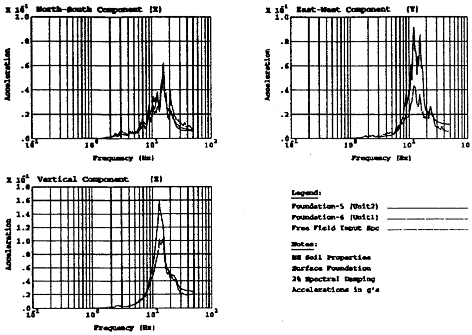
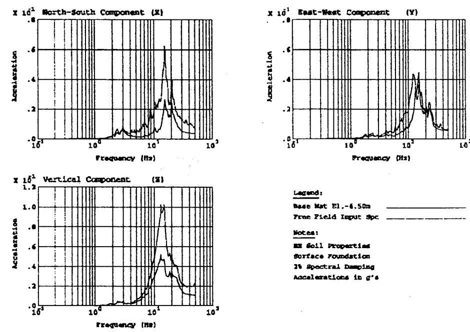


Fig.7 Comparison of Strip Foundations Input Motion with Free Field Motion

Fig.8 Comparison of Base Mat Input Motion with Free Field Motion



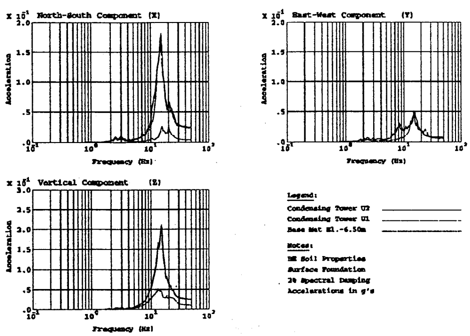


Fig.9 Comparison of Condensing Towers Responses with Base Mat Motion

Fig.10 Comparison of Reactor Hall Responses with Base Mat Motion