17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

FREQUENCY-ADAPTIVE GRILLAGE TECHNIQUES FOR SEISMIC ANALYSIS OF NUCLEAR CONTAINMENT STRUCTURES

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Abstract

The current state of practice for analysis of nuclear containment structures is based mostly on two methods: the Finite Element Method (FEM) and the Lumped Mass Stick (LMS) method. These two techniques are very different from each other, as FE models deliver very accurate results but require a substantial amount of time and computational power; while LMS is much less complex, to the expense of a lower accuracy of results. This research tries to fill this gap by proposing a new method of modelling for analysis of nuclear containment structures based on a frequency-adaptive grillage technique.

The paper compares the results obtained from a modal and non-linear time history seismic analysis between the different modelling techniques. These analyses highlighted that the new grillage model results in a much faster and less complex modelling process, while requiring much less computational power than FE models. It also produces results that are consistently more accurate than the LMS model to which it was compared. Finally, suggestions on how this model can be improved are made.

Keywords: Nuclear; Containment; Grillage; Frequency-adaptive; Nonlinear analysis

1. Introduction

One of the biggest problems societies are facing in the 21st century is that of the continuously increasing energy demands. Carbon-based fuels such as coal, oil and natural gas, although still widely used, are slowly being replaced by more renewable forms of energy. Nuclear energy fits into this last category, and while offering great potential in terms of energy production, the growing number of Nuclear Power Plants (NPP) being built have increased the concern for safety, as structural damages to nuclear reactors may have catastrophic consequences [1].

In order to analyse the behaviour of Nuclear Containment (NC) structures subject to seismic loading, Finite Element Analysis (FEA) [2] is usually used. This standard is employed in the analysis of both new structure designs as well as in the assessment of existing structures [3]. This type of analysis is known to deliver very accurate results. However, it requires a lot of computational power, and in the analysis of complex problems, it is still considered expensive and time consuming [4].

Different types of lumped-mass stick models have also been tested to varying degrees of accuracy. These models are mainly applied as a simplified technique for complex column-typed structures such as nuclear containment buildings [5]. In the LMS model, the lumped masses are usually determined by looking at the tributary area. An attempt to modelling a Containment Structure and the Internal Structures using this method was done by Y. Huang et al. [6] with success. However, the "Lumped Mass Stick Model" used by them may be considered over simplistic for many purposes.

In recent years, research was done on ways to make the LMS models better simulate the dynamic behaviour of NPP, such as the "Frequency Adaptive Lumped Mass Stick Model" as proposed by H. Lee [7], which takes into consideration the dynamic properties of the structure resulting in a model of a structure with the same natural frequencies as the actual structure.

The model developed in this paper uses the principles of the "Frequency Adaptive Lumped-Mass Stick Model" [7] but uses grillage techniques [4, 8] to develop a model in the 3D plane to better capture the geometric properties of the NC.

2. Models

Four models were developed and compared:

- 1 Solid Elements model (Model 1)
- 1 Lumped mass stick model. (LMS, Model 2)
- Grillage model 36 verticals (GM1, Model 3)
- Grillage model 8 verticals (GM2, Model 4)

The geometry of the NC structure considered in this project is shown in Figure 1. The height of the containment is of 75m and the outer diameter is 50m with a wall thickness of 1.22m.

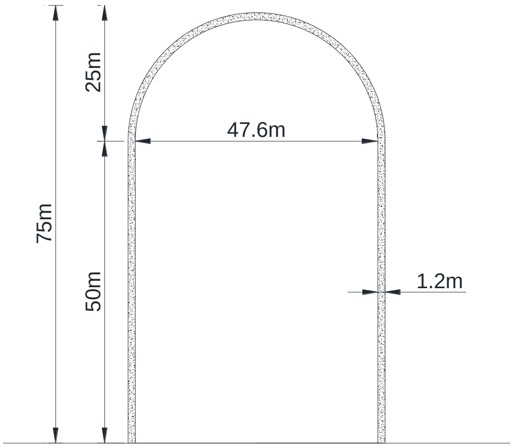

Fig. 1 - Dimensions

For all models, concrete C35/45 was used. The Young's and Shear modulus applied are 34.00GPa and 14.17GPa, respectively. The total mass of the NC M_{tot} is 34,220,000 kg. The mass of the dome and cylinder structure are presented in Table 1.

Table 1- Volume and Mass of CS

Structure	Volume (m^3)	Mass(kg)
Cylinder	9,198	22,995,000
Dome	4,490	11,224,537
Total	13,688	34,220,000

A time-history function of the east-west component of the "El Centro" earthquake was imported into the software SAP2000. The load was applied to all the models as a ground acceleration, acting in the x direction. A scaling factor of 9.81 was applied, as the accelerations are given in terms of "g". The theory of grillage modelling coupled with that of the Frequency Adaptive LMS was used to develop a new way of modelling a nuclear containment structure aiming to better represents the behavior of the NC building when compared to the stick models, while still being much less computationally intensive than the shell FE model.

Two grillage models were analysed, one where the ratio between the number of vertical elements and perimeter is 1:4 (Model 3) and one where it is 1:17 (Model 4). For both the models, the ratio between the number of horizontal elements and meter rise is 1:1, as this was found to give the most accurate results.

The model consists of a series of vertical beam elements (columns) set around the perimeter of the structure, connected by horizontal elements (beams) to simulate the behavior of the wall of the cylindrical structure and the dome.

The geometrical properties of the columns should be so that the following is achieved:

$$I = \frac{(t \cdot L_p^3)}{12} \quad [1]$$

$$A = t \cdot L_p \quad [2]$$

Where:
I - is the moment of inertia.

t - is wall thickness of the NC structure.

Lp - is the width of the portion of wall that the column simulates.

This applies to both the columns representing the cylinder and the dome. However, for the dome structure, these are set at an angle forming an arch, in order to better capture the behavior of the dome (as can be seen in Figure 2). The beams are then modelled as rigid links.

Convergence analysis showed that the ratio of the number of beams per meter rise should be no less than 1:2. Furthermore, the mass of the structure should be applied at specific nodes, which are found using the same procedure as described by H. Lee et al (2012). The cylindrical structure is analyzed separately, and the dome can be accounted for by applying a lumped mass at the topmost node.

Like for the "Frequency Adaptive Lumped-Mass Stick Model", the grillage model requires the results obtained from a modal analysis of a FEM model to find the location of the mass nodes. However, instead of performing the analysis on the NC as a whole, only the cylindrical structure is analyzed, the dome is then accounted for by applying its mass to the top node of the grillage model. This not only simplifies the modeling process, but also gives more accurate results. The location of the node masses for the cylindrical structure were found as can be seen in Fig. 3.

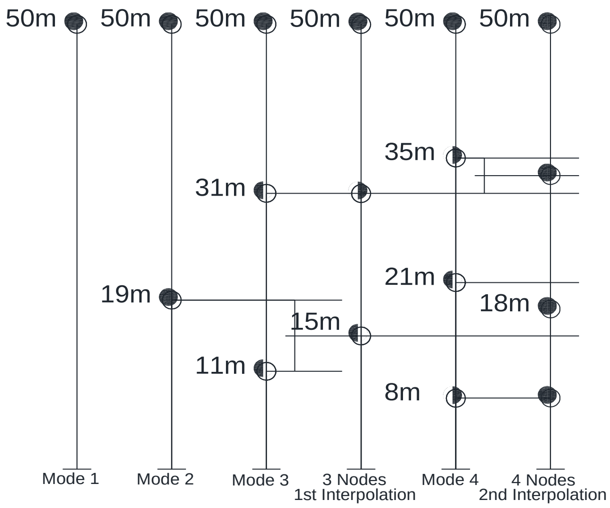

Fig. 2 - Interpolation of Masses [7]

From the modal analysis of the cylinder, it was found that modal participation ratio exceeded 90% after the fourth mode; so, each column element was assigned 4 masses plus the additional mass of the dome.

The section properties of the column were assigned taking into consideration the geometrical properties of the section of wall that they represent. In the case of model 3, the perimeter of the structure was divided into 36 segments, meaning that each column has an Lp = 4.4m. The beams were modelled as rigid links, restricting their degrees of freedom in every direction. The ratio between the number of beams and meter rise was kept as 1:1, for each division. All sections were C35/45 as described above. The structure was assumed to be fully fixed to the ground and the ground floor nodes were assigned encastre boundary conditions.

Unlike what was done for the LMS method, no iterative procedure was required to find the magnitude of the mass to apply at each node. For the columns corresponding to the cylindrical structure, the total mass of the cylinder was divided by the number of nodes to which a mass was to be assigned (144 nodes for this model). On the other hand, for the dome, a lumped mass corresponding to that of the mass of the dome was applied to the topmost node.

3. Results

The below table shows the results obtained by the modal analysis for each model.

Table 2 - Comparison of T1-4

Mode	T1-4,FEM (s) (Benchmark)	T1-4,LMS(s)	T1-4,GM1 (s)	T1-4,GM2 (s)
1	0.234	0.240	0.237	0.237
2	0.078	0.068	0.070	0.066
3	0.038	0.041	0.037	0.051
4	0.030	0.032	0.030	0.031

It can be seen that the fundamental time period, T1, of all three models is very close to that of the FE model, proving that the three different models have similar dynamic behaviour

A similar pattern can be seen when comparing results for Displacement, Acceleration and Base Reactions. Displacement graphs obtained from the time-history analysis are shown below (Figs. 3 and 4)

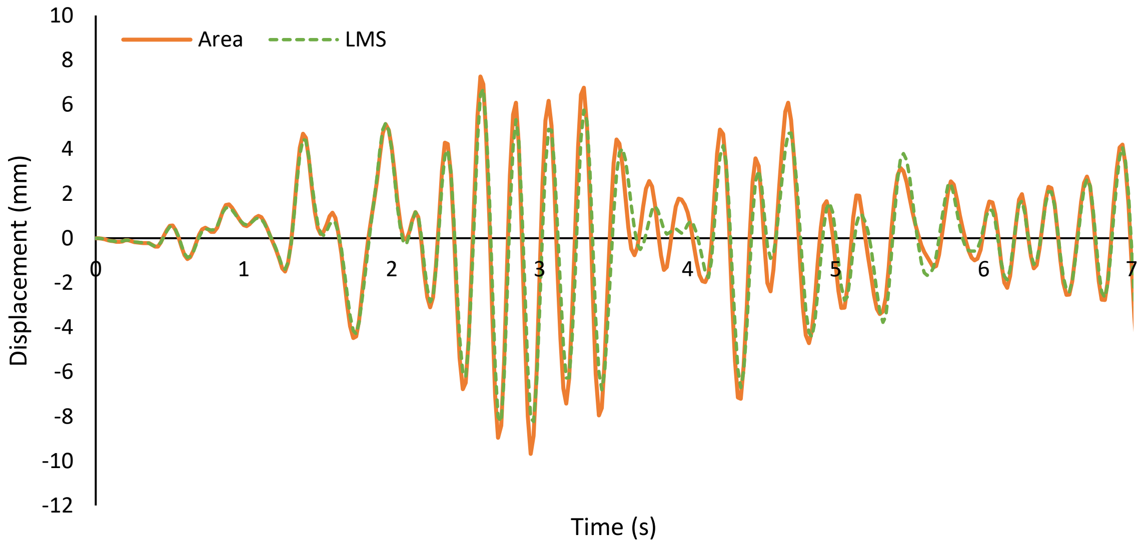

Fig. 3 - Displacement Comparison – 4th Floor – FEM and LMS

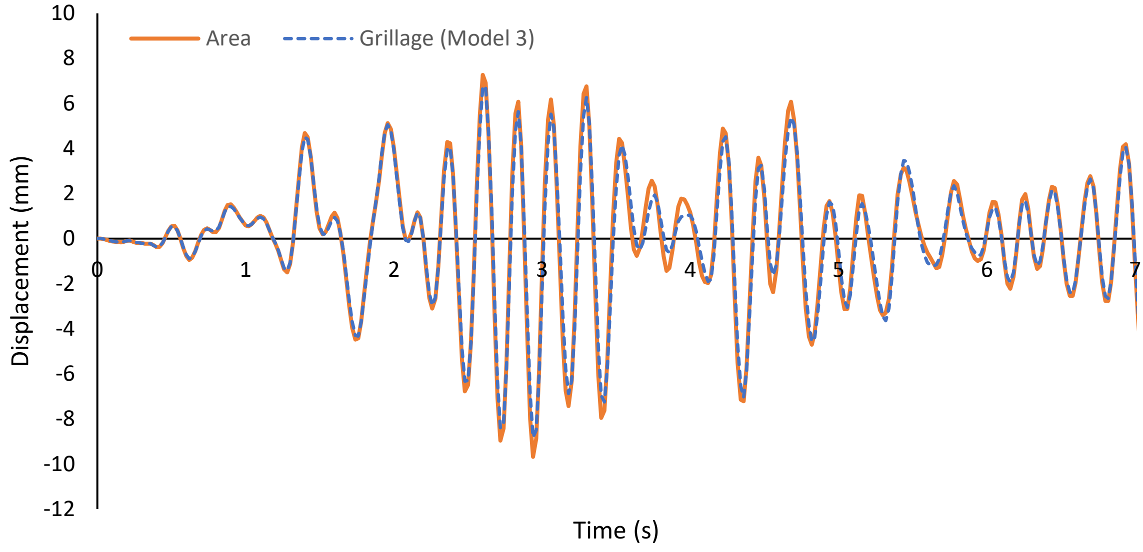

Fig. 4 – Displacement Comparison – 4th Floor – FEM and Grillage

As can be seen the models capture the dynamic behaviour of a nuclear containment structure subject to seismic loading.

A similar trend can be seen when looking at results for acceleration and base reactions. Below are the graphs comparing these two aspects against time for all models (Fig.5 and Fig.6)

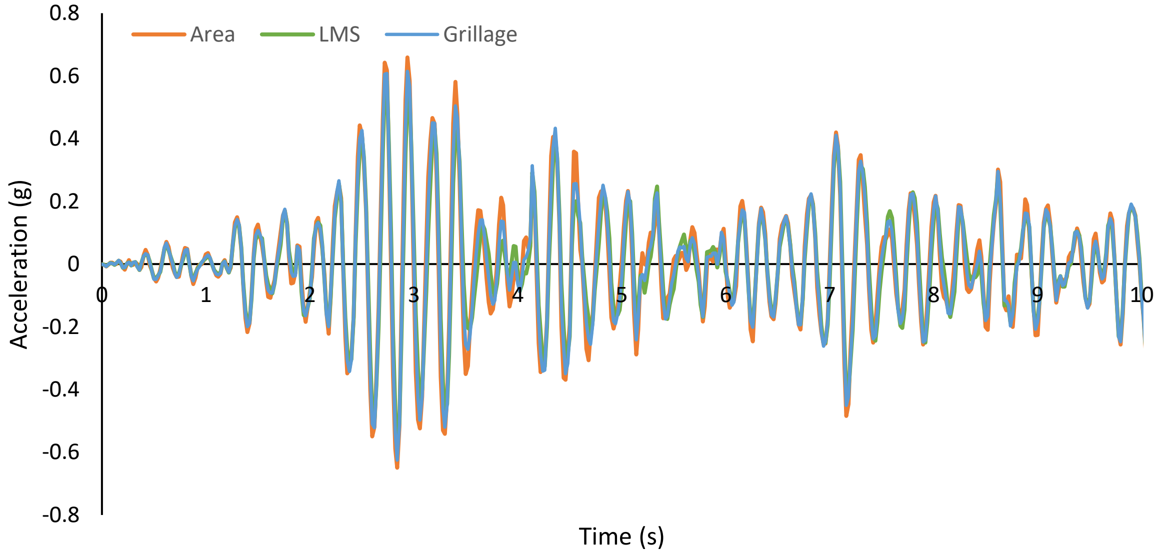

Fig. 5 – Acceleration Comparison – 4th Floor – All Models

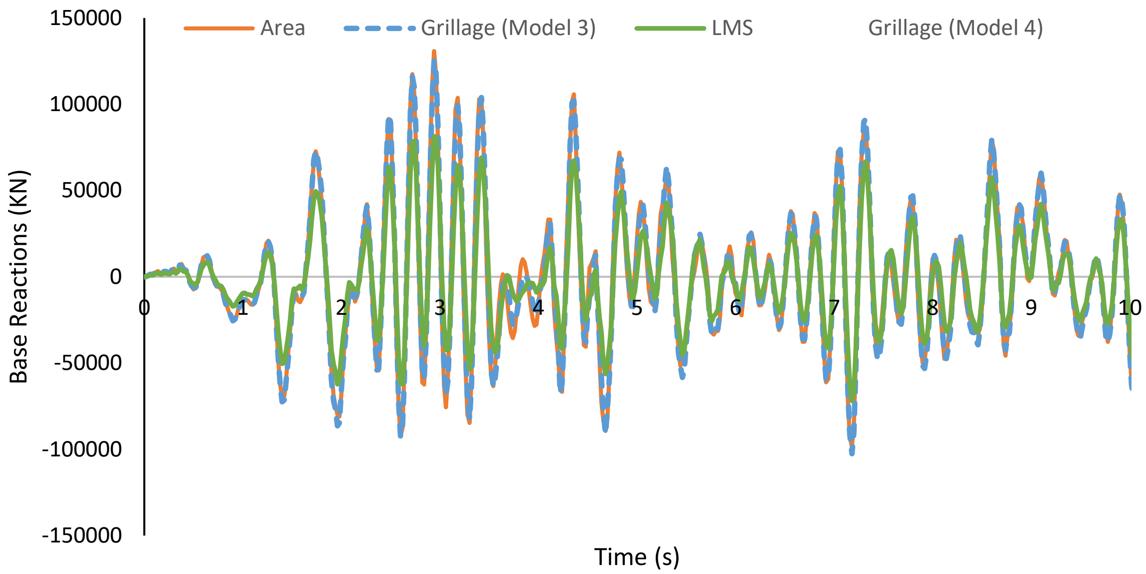

Fig. 6 – Base Reaction Comparison – 4th Floor – All Models

The model that better captures the dynamic response of the NC was Model 3, whose peak values for displacement, acceleration and base reaction were 91%, 95% and 96%, respectively, of the benchmark FE Model 1. Considering the simplicity of the model, and the speed of the analysis time when compared to Model 1 (up to 100x faster analysis), these results show a great level of accuracy.

Model 4 produced a graph that was consistently identical to that of Model 3, however scaled down to some degree. For this reason, it better captured the overall behaviour of the structure compared to Model 2, but underestimated the peak absolute values, reaching an accuracy of 71% and 84% for peak displacement and acceleration, respectively.

Below is Table 3, presenting peak top floor displacement, acceleration and base reactions for all 4 models.

Table 3 - Comparison of Peak Top Floor Parameters

Parameter	Model 1 (Benchmark)	Model 2 (LMS)	Model 3 (Grillage)	Model 4 (Grillage)
Displacement (mm)	9.683	8.232	8.816	6.914
Acceleration (g)	0.659	0.582	0.625	0.5521
Base Reaction (KN)	130832	86544	125047	96700

The newly developed grillage model constantly delivered more accurate estimates of the behaviour of the NC when compared to its LMS counterpart. The results of all the parameters investigated were within a 10% range of those obtained by the more complex FE model, and computational time was immensely reduced. Furthermore, as the grillage model did not require any lengthy iteration procedure when assigning the nodal masses, which is required for the LMS model, the modelling phase was also reduced to a minimum.

4. Conclusion

The main aim of this project was to develop a model that is simpler in nature than the FE models, using only 1D elements, providing quicker analysis and requiring less computational power, while still delivering consistent and reliable results.

To this aim, a new type of model was developed, merging elements from the theory of grillage techniques, which are often used in bridge deck analysis, and the new frequency-adaptive modelling techniques employed for certain Lumped Mass Stick models.

To benchmark the results obtained by this model, an FE and an LMS model were also created. Modal and time-history analysis were then performed on all models, subjecting them to the "El Centro" ground acceleration. Results for periods, displacements, acceleration and base reactions were then compared.

It appeared that the newly developed grillage model constantly delivered more accurate estimates of the behaviour of the NC when compared to its LMS counterpart. The results of all the parameters investigated were within a 10% range of those obtained by the more complex FE model, and computational time was immensely reduced (100x faster). Furthermore, as the grillage model did not require any lengthy iteration procedure when assigning the nodal masses, which is required for the LMS model, the modelling phase was also reduced to a minimum.

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