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Modelling of Turbine-generator and Foundation as Single Degree of Freedom Using Ruaumoko Programme

Shafii Abdullah, Nor Hayati Abdul Hamid

Abstract*– A rigid-moment frame supporting the turbine-generator was designed according to BS 8110. This structure is subjected to vibrations of turbine-generators and seismic loading. Turbine-generator with its foundation is model as a single degree of freedom (SDOF) using RUAUMOKO program. RUAUMOKO program is employed in this study to analysis non-linear dynamic behaviour of turbine foundation using time-history analysis and Modified Takeda Model. Mode shape, natural period, natural frequency, nodal displacement, member forces and moment of reinforced concrete turbine foundation were obtained by running this program. The result shows that turbine foundation under Imperial Valley earthquakes does not exceed yield drift limit for monolithic connection and remain within the elastic condition. Thus, RC turbine foundation is safe and able to carry gravity load as designed according to BS 8110. Contradictory, turbine foundation experience exceeding yield drift limit but it is not safe and likely to collapse under San Fernando earthquake loading.

Keywords: turbine-generator, turbine foundation,non-linear dynamic analysis, time-history analysis, yield drift limit.

I. INTRODUCTION

Turbine-generator with highly concentrated mass located on top of a rigid-moment reinforced concrete frame acting as supporting system. The RC frame and turbine generator is subjected to vibration during operation hours. The vibration becomes significant to RC frame especially when the top deck is supported by slender columns which may be subjected to a lateral force at the top due to rotation of the turbine-generator parts during starting up the machine. These vibrations may be induced by machine vibrations, earthquake excitation in medium and high seismic regions or from constructional activities.

Potentially, these combinations of vibrations can cause structural damage or even structural collapse especially under strong ground motion. Although strong earthquakes are not likely to occur in low to medium seismic regions but the turbine foundation still expose to ground excitations either near-field or long distance earthquakes.

Figure 1 shows the typical isometric view of rigid-moment RC frames of the turbine foundation with turbine-generator machine placed on top of it. Figure 2 shows front elevation of the typical rigid-moment RC frame turbine foundation.

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***** Correspondence Author (s)
Shafii Abdullah, Postgraduate Student, Faculty of Civil Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia.
Nor Hayati Abdul Hamid, Associate Professor, PhD, Faculty of Civil Engineering, Universiti Teknologi MARA,Shah Alam, Selangor, Malaysia.

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Small lateral loads come from minor earthquakes are usually resisted within the elastic range and intrinsic damping of concrete in turbine foundation. However, moderate and severe earthquakes behave beyond the elastic limit and elastic behaviour is developed especially at their connections. The RC frame is designed to resist gravity loads comprising self-weight, superimposed weight and vibration loading from the turbine-generator. However, earthquake loading is not considered as in-line with no provision of earthquake loading in BS 8110.

The intention of this research is to determine seismic performance of rigid-moment RC frames under three past earthquake records by modelling it as single degree of freedom (SDOF) using Ruaumoko program. It is believed that this structure can survive under minor earthquake because the elastic lateral strength capacity of the structure is able to resist the small lateral load which comes from earthquakes. By modelling this structure using time-history analysis and non-linear behaviour together with Ruaumoko program, the dynamic parameters can be determined and the global stability of the structure can be predicted. The structural dynamic parameters such as mode shape, natural period, natural frequency, hysteresis loops, nodal displacement of the node, members' forces and moments can be determined by using Ruaumoko program. The static and dynamic solutions can be formulated and solved using this useful program and these solutions are beneficial to the structural civil engineers to improve on the design, construction and maintenance aspects of the turbine-generator together with its raft foundation.

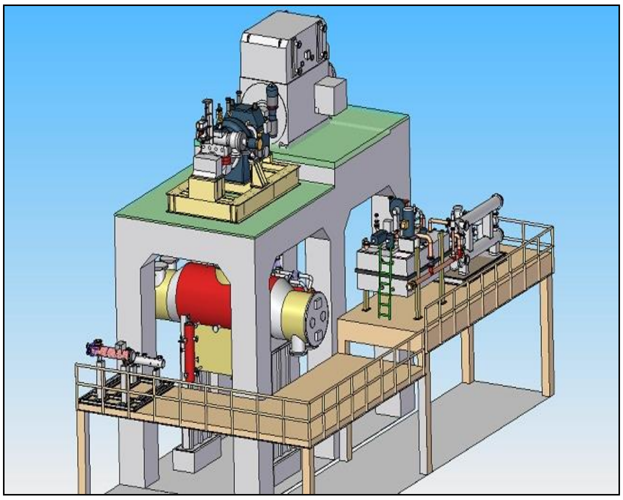

Figure 1: Typical RC-frame turbine foundation.

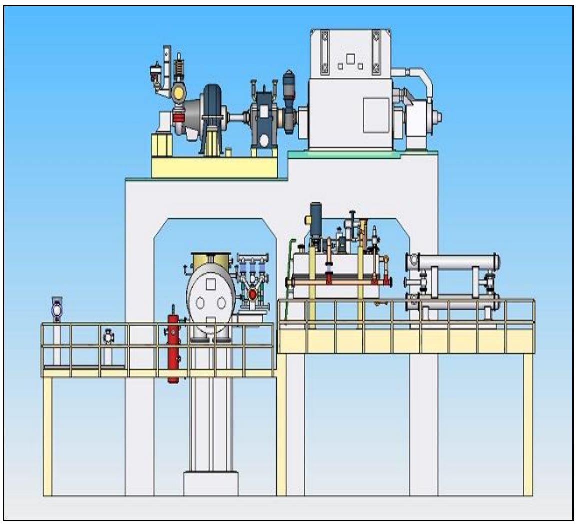

Figure 2: Front elevation of RC-frame turbine foundation.

II. TURBINE-GENERATOR AND ITS FOUNDATION

The turbine-generator becomes the heart of a power plant. It is the most vital and expensive equipment in the power plant complex and it is placed inside the Turbine House. RC turbine-generator floor comprised of top deck, supporting structure and a raft foundation system. All the equipment of power plant including turbine, generator, governor and other mechanical-electrical instruments are located on top of the deck. The top deck is divided into two areas where to place the turbine and generator, separately. This foundation consists of a raft directly resting on strong soil or resting on piles if the soil is soft. Based on the functionality and stability requirements, the top deck and supporting structure frame are constructed monolithically.

The growth of electricity consumption in the world in conjunction with evolving environmental requirements and it is expected that the fossil fuel price increases inspires the current production of renewable energy thermal combined with re-cycle power plants. Livshits [1] further stressed that the turbine-generator foundation is a complex engineering structural component. Different types of turbine foundation are used for different machines depending on their capacity, geometrical sizes and constructional features. The turbine foundation with base slab may rest directly on soil or may be supported by piles. Dynamic behaviour of the foundation plays an important role in providing normal operating conditions for the supported turbine-generator. In high seismic regions, seismic forces are extremely significant to be included as lateral load when designing the turbine foundation.

Bhatia [2] pointed out that examination of the dynamics of the machine-foundation system is very important and the consideration of earthquake effects further adds to its complexity. The performance, safety and stability of machines depend largely on their design, manufacturing and interaction with their supporting frame. In this case, the foundation system should be able to resist earthquake loading up to the safety limit without collapse. Significant damage to machinery has been reported for many past earthquake occurrences in the world. Thus, Bhatia [2] recommended that the vertical seismic coefficient be equated to the horizontal seismic coefficient in application to machine-foundation in order to get better performance for the systems.

III. RUAUMOKO PROGRAM

Ruaumoko Program was developed by Carr [3] and the word RUAUMOKO was borrowed from local legend of the Maori God of volcanoes and earthquakes. The Ruaumoko program is designed to produce a piece-wise time-history response of non-linear of two-dimensional and three-dimensional structures subjected to ground displacement or time varying force excitations. The program may also be used for static and pushover analysis of various types of structures. Ruaumoko program is one of the most popular programs available to carry out time history analysis for two or three dimensional frame structures, which have a loading input and a discretely defined acceleration record. Several different options are available for modeling of the mass, damping and stiffness matrices for the structure. This program contains various types of hysteresis loops model to represent the actual structural behaviour of the system. These hysteresis loops model were compared with the experimental hysteresis loops obtained from laboratory work. For modeling the behaviour of RC frame, the most appropriate hysteresis model would be Modified Takeda, or Stiffness Degrading Model. There are also more complex hysteretic elements such as Fukada Degrading Tri-linear hysteresis which available for more refined analysis.

IV. MODELING PROTOTYPE TURBINE USING RUAUMOKO 2D

The structure creation and result visualisation is done using standard text-editors such as Microsoft Windows Notepad. FORTRAN language is used to solve the bigger matrix which involves a lot of unknowns. One input text file needs to be created before running the RUAUMOKO 2D programme [4]. Figure 3 shows the flow chart of the procedure involves in preparing data input, running RUAUMOKO 2D programme and obtained the output from DYNAPLOT programme which is part of Ruaumoko program.

V. ANALYSIS OF RESULTS

The analysis of results includes the comparison of results obtained from DYNAPLOT and RUAUMOKO 2D programme. The results consists of earthquake excitations, spectral displacements, pseudo spectral acceleration, plotting of the structure, deformation shape of the structure and hysteresis loops at beam-column connection of the turbine foundation.

The results showing the behaviour of elements in rigid-moment turbine foundation will be discussed in the following sub-topics.

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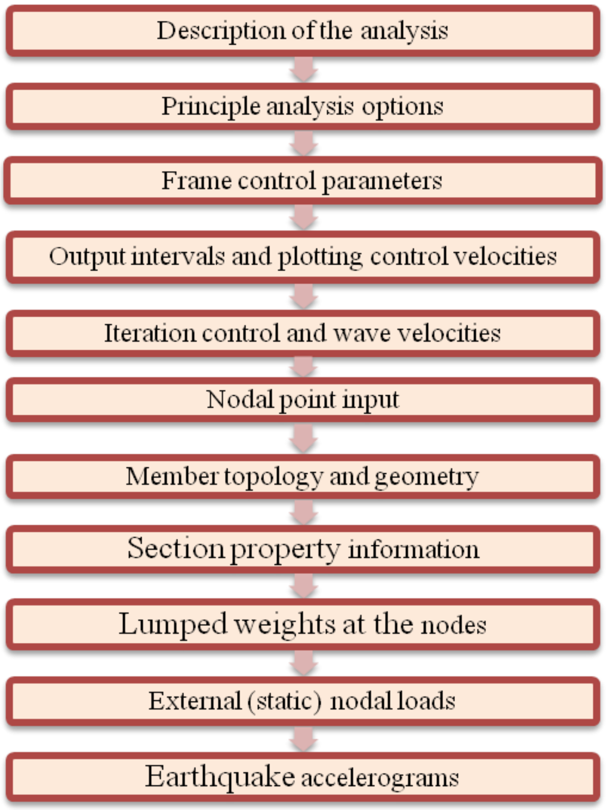


Figure 3: Work sequence for finite element analysis using RUAUMOKO 2D programme.

A. PAST EARTHQUAKE RECORDS

Three earthquake excitation records were chosen to run the model. Currently, Malaysia does not have any established database on recent earthquakes in Malaysia or the local effects of earthquakes in the surrounding region. In this regard, three past earthquake time-history records have been selected for the purpose of this modelling. The three chosen earthquake records selected to run the model of the turbine foundation are as listed below:

(a) 1940 Imperial Valley Earthquake (El Centro North-South component, EL40NSC)
(b) 1940 Imperial Valley Earthquake (El Centro East-West component, EL40EWC)
(c) 1971 San Fernando Earthquake (PACMSW)

The characteristic of the selected past earthquake records in term of magnitude, peak ground acceleration (PGA), duration, depth and location are present in Table 1.

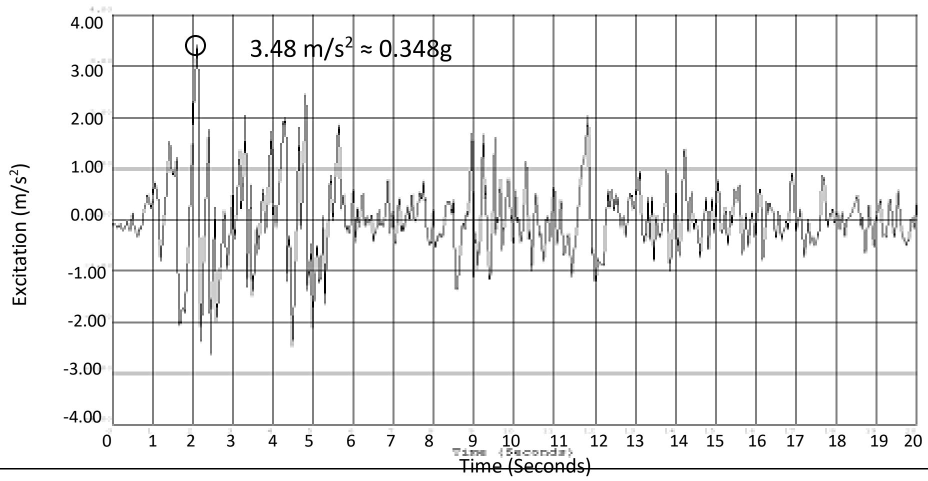
Table 1: Characteristic of the selected past earthquake records

Earthquakes	Magnitude	PGA	Duration	Depth	Location
EL40NSC	7.1	0.348g	32 seconds	6 km	El Centro NSC
EL40EWC	5.5	0.214g	30 seconds	6 km	El Centro EWC
PACMSW	6.6	1.170g	60 seconds	8.4 km	Pacoima Dam

Table 2 shows the output of DYNAPLOT for earthquake excitation of the selected earthquakes. Maximum excitation within a period of 20 seconds for each of the chosen earthquake events, ranked from highest to lowest value is:

- PACMSW 11.70 m/s^2 or 1.17g
- EL40NSC 3.48 m/s^2 or 0.348g
- EL40EWS 2.14 m/s^2 or 0.214g

Table 2: Earthquake excitation

Earthquakes	Earthquake Excitation
EL40NSC	

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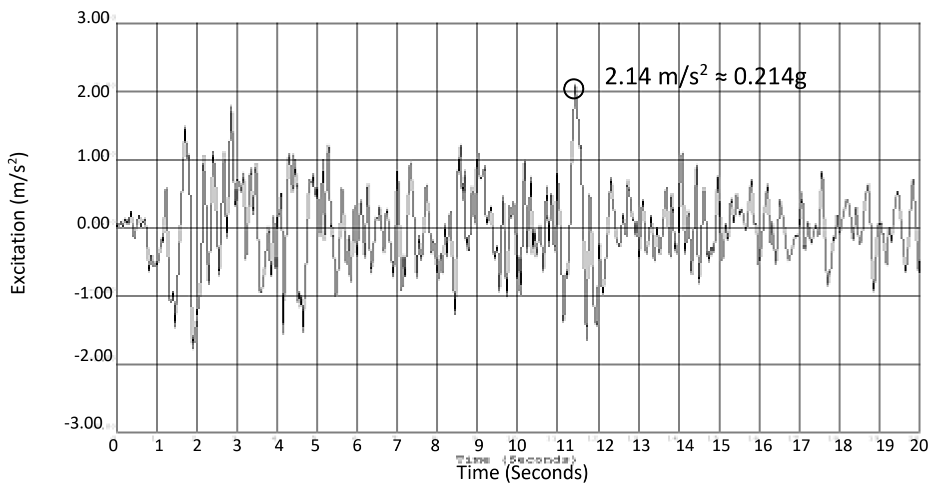
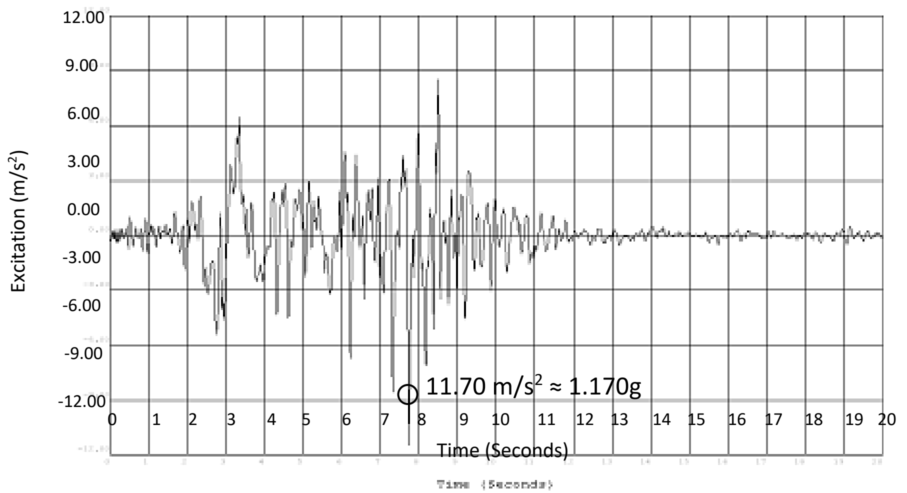
EL40EWC	
PACMSW	

Table 3 shows the spectral displacement of a structure with various percentage of damping. For the three chosen earthquakes it shows that the displacement caused by three earthquakes, ranked from highest to lowest value is the structure without damping has bigger displacement. Pseudo spectral acceleration for the structure shown in Table 4 has also indicated that structure without damping (ξ=0%) has accelerated more as compared to the structure with damping. Maximum pseudo spectral acceleration for the structure under the effect of the three chosen earthquake events, ranked from highest to lowest value is:

- PACMSW 9.99g at 0.45 seconds
- EL40NSC 6.72g at 0.45 seconds
- EL40EWC 4.74g at 0.40 seconds.

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Table 3: Spectral displacement

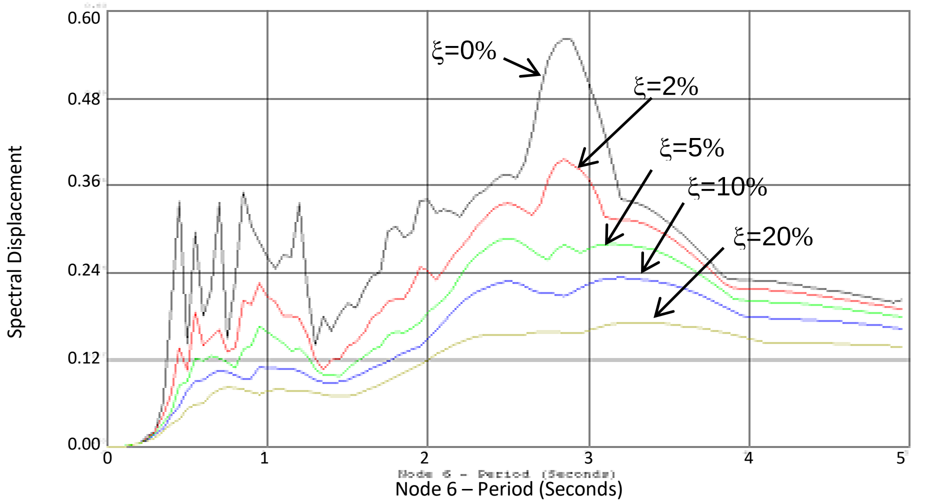
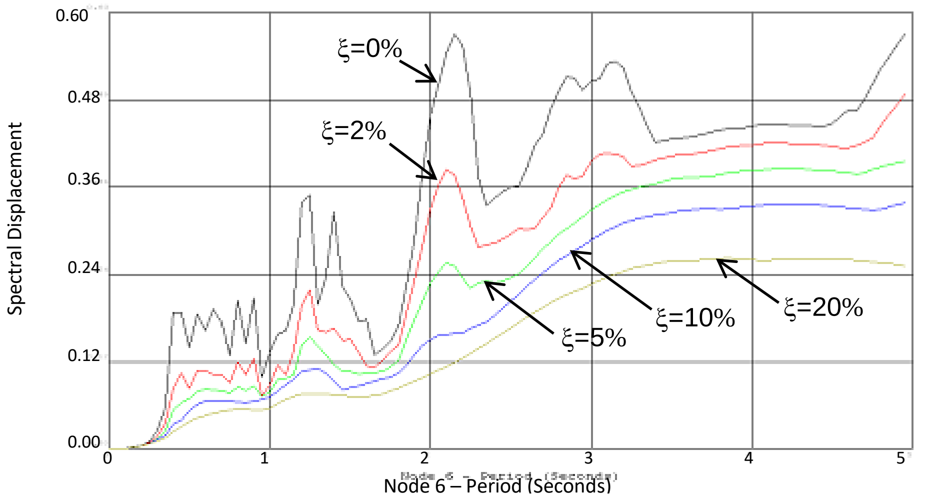
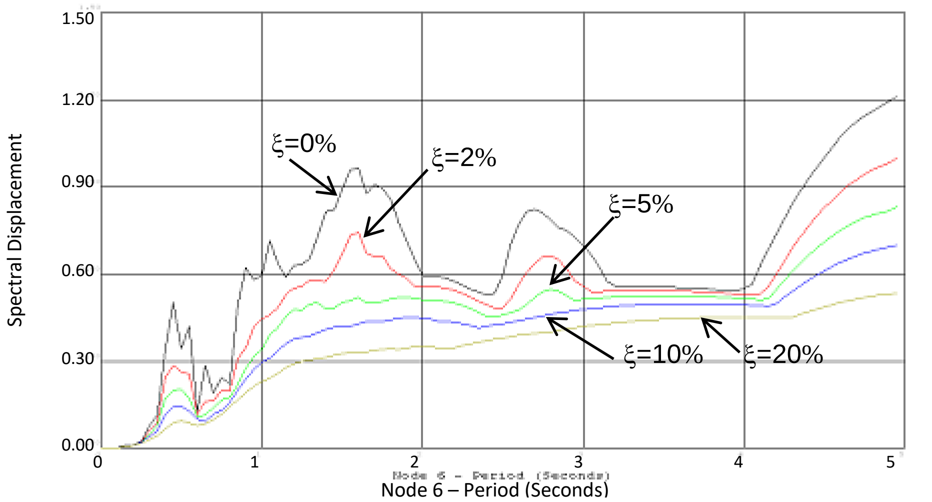
<table>
<tr><th>Earthquakes</th><th>Spectral Displacement</th></tr>
<tr><td>EL40NSC</td><td>
</td></tr>
<tr><td>EL40EWC</td><td>
</td></tr>
<tr><td>PACMSW</td><td>
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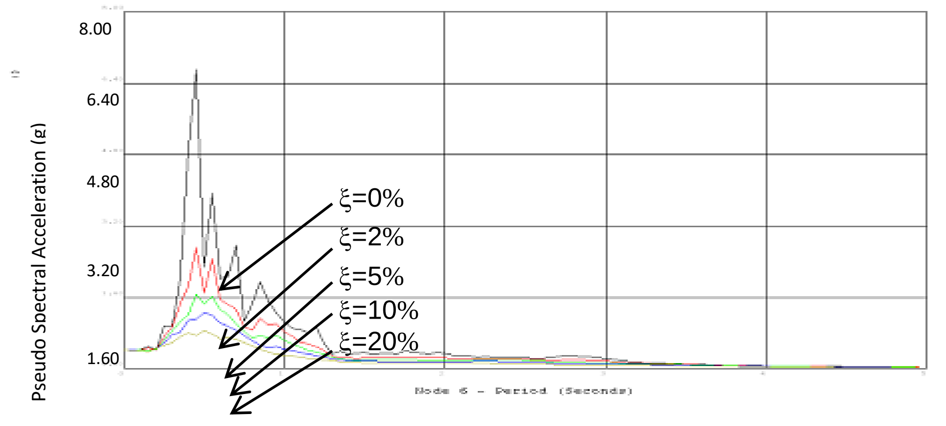
Table 4: Pseudo spectral acceleration

<table>
<tr><th>Earthquakes</th><th>Pseudo Spectral Acceleration (g)</th></tr>
<tr><td>EL40NSC</td><td>
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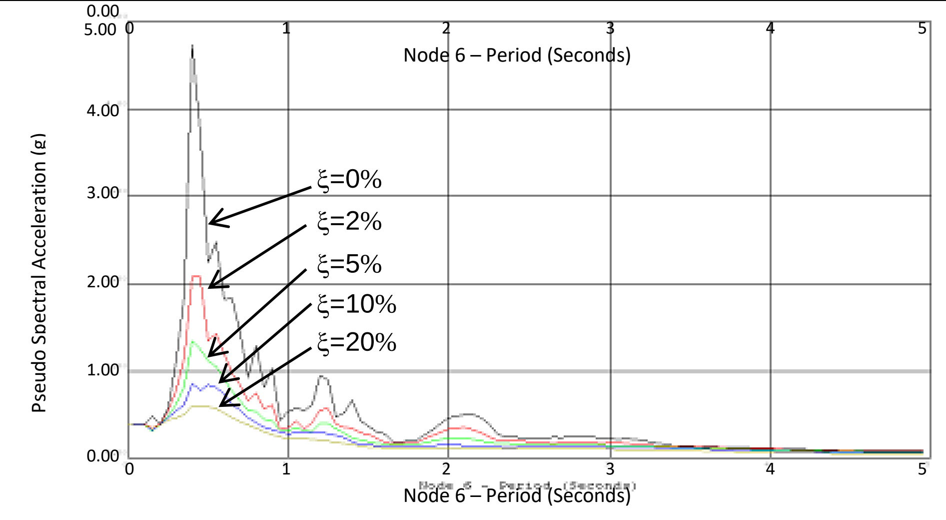
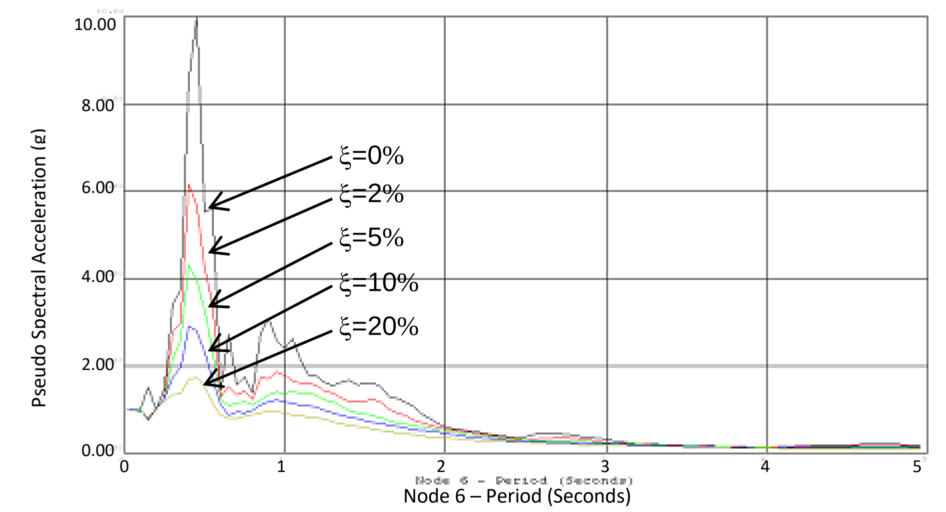
<tr><td>EL40EWC</td><td>
</td></tr>
<tr><td>PACMSW</td><td>
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B. PLOT OF THE MODEL STRUCTURE

The prototype of turbine foundation for a biomass power plant is modelled using RUAUMOKO program subjected to three past earthquake records. This type of structure forms a rigid-moment resisting frame with monolithic connections. The connections are assumed to be rigid at beam-column interface and column-foundation interface. Both of these interfaces can be represented as node in turbine foundation frame. The turbine supporting frame is presented by six (6) nodes and five (5) elements as shown in Figure 4. The earthquake loading is applied at ground level which caused the frame to experience the highest deformation at nodes 4, 5 and 6.

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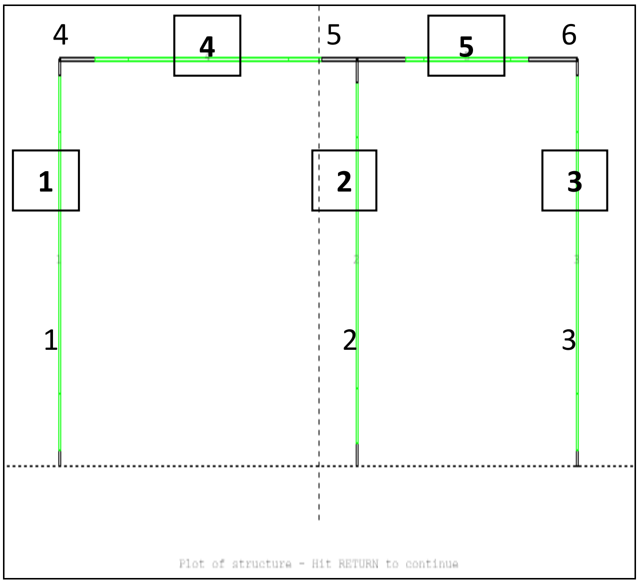

Figure 4: Location of nodes and elements in turbine supporting frame

VI. DEFORMED SHAPE OF RC FRAME

The total mass of generator and turbine at top deck can be represented as lump sum mass in Ruaumoko program. As a SDOF system, there is only one mode shape denoted as Mode Shape 1. This structure can move in positive or negative x-direction with lateral deformation. The deformed shape of turbine foundation frame under three selected past earthquake excitations is analysed using time-history analysis with dynamic solution.

A. DYNAMIC SOLUTION

The model of turbine-generator subjected to three different earthquakes namely EL40NSC, EL40EWC and PACMSW. Table 5 shows the first mode shape, duration and frequency of the frame under three earthquakes loading. Natural frequency for mode shape 1 under dynamic solution for three chosen earthquake accelerograms is 2.94 Hz with damping factor of 5%. During earthquake excitations, the moment-rigid frame sways repeatedly to the left and to the right of the turbine foundation in opposition to the ground motion. Within each sway cycle, the concrete column experiences the changing of compression zone to tension zone and come back to tension and compression zone. This repetitive change will definitely affected the strength and durability of the columns. It is well known that concrete is strong in compression and weak in tension. These cyclical swaying effects have resulted in severe damage and partial collapse of the frame under PACMSW accelerograms. Under PACMSW accelerograms, the plastic hinge zone occurs in beam-column joint and the lateral seismic force is exceeding the lateral strength capacity of the structure. More plastic hinges zone occur in columns under PACMSW earthquake excitation (marked as red colour in Table 5) and causing damages and instability (near collapse) of the turbine foundation frame.

B. NODAL DISPLACEMENT

Table 6 shows the top node displacements of this frame for mode shape 1 at Node 4, Node 5 and Node 6 under three earthquake records. The maximum lateral displacement (x-direction) of 62.13mm was determined in the frame under PACMSW earthquake for Node 4, Node 5 and Node 6 with the same time of 7.92 seconds.

It is noted that for all cases, the y-component of displacement varies in magnitude from 0.02mm to 0.27mm and these values are considered negligible. The significant displacement is in the x-direction (to the right), and is expressed both in mm of node shift and as a percentage of the structure's length in the x-direction, described as positional drift. The maximum x component of node displacement for each of the three chosen earthquake events, ranging from highest to lowest value is:

- PACMSW 62.13 mm at 7.92 seconds elapsed time, equivalent to 0.8% positional drift
- EL40NSC 24.00 mm at 5.08 seconds elapsed time, equivalent to 0.3% positional drift
- EL40EWC 17.12 mm at 2.04 seconds elapsed time, equivalent to 0.2% positional drift

An important conclusion that is highlighted by the analysis is that structural maximum displacement is in proportion to peak ground acceleration but not necessarily in proportion to magnitude of the earthquake as measured by the Richter scale [5].

For the structure to remain within the elastic condition, positional drift should not exceed yield drift of 0.4% for monolithic connection. Based on the percentage of positional drift presented above, the turbine foundation under EL40NSC and EL40EWC excitation is found to be safe and sound. Under PACMSW excitation the turbine foundation has drifted 0.8% which is 50% in excess of yield drift limit for monolithic connection. Therefore, it can be concluded that the turbine foundation under PACMSW excitation will not be safe and is likely to collapse.

C. MEMBER FORCES

Table 7 shows the axial forces, vertical forces and moments in each structural member of the frame under three earthquake excitations. The forces consist of axial forces, moments and shear forces and the maximum values of these forces are:

- Axial forces, 561.8 kN recorded at Member 2 under EL40EWC.
- Moment, 2712.0 kNm also recorded at Member 2 but under PACMSW.
- Shear force, 787.4 kN recorded at Member 5 under PACMSW.

Comparison of member forces under the three earthquake shows that Member 2 under PACMSW is in a very critical condition and fails in bending.

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Table 5: Mode shape under dynamic solution

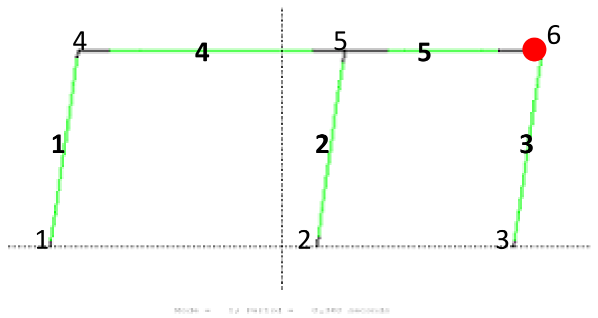
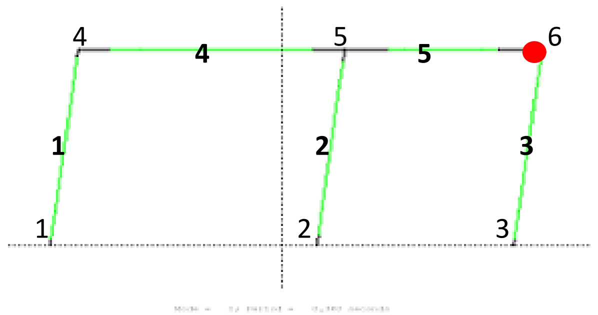
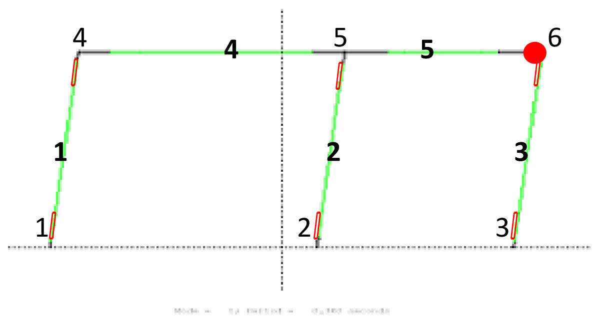
Earthquakes	Mode Shape	Duration (s)	Frequency(Hz)
EL40NSC		0.34	2.94
EL40EWC		0.34	2.94
PACMSW		0.34	2.94

Table 6: Node displacement for Node 4, Node 5 and Node 6

Earthquake	Node 4				Node 5				Node 6			
	Δx (mm)	t (s)	Δy (mm)	t (s)	Δx (mm)	t (s)	Δy (mm)	t (s)	Δx (mm)	t (s)	Δy (mm)	t (s)
EL40NSC	24.00	5.08	-0.15	5.08	24.00	5.08	-0.25	5.08	24.00	5.08	0.02	2.16
EL40EWC	17.12	2.04	-0.17	2.03	17.12	2.04	-0.27	11.78	17.12	2.04	-0.02	11.52
PACMSW	62.13	7.92	-0.02	7.92	62.13	7.92	-0.12	7.92	62.13	7.92	0.23	8.60

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Table 7: Member forces

Earthquakes	Member 1 (Column)	Member 2 (Column)	Member 3 (Column)	Member 4 (Beam Deck)	Member 5 (Beam Deck)
EL40NSC	Ax= -195.6kN M1=525.5kNm M2=475.6kNm V1=145.1kN V2=145.1kN	Ax= -510.4kN M1=1185.0kNm M2=1291.0kNm V1=339.5kN V2=339.5kN	Ax= 22.02kN M1=427.4kNm M2=630.2kNm V1=118.5kN V2=118.5kN	- M1=394.7kNm M2=412.8kNm V1=163.7kN V2=163.7kN	- M1=602.1kNm M2=191.6kNm V1=359.8kN V2=359.8kN
EL40EWC	Ax= -224.3kN M1=515.8kNm M2=409.5kNm V1=143.0kN V2=143.0kN	Ax= -561.8kN M1=1030.0kNm M2=978.1kNm V1=297.5kN V2=297.5kN	Ax= -22.21kN M1=345.2kNm M2=477.7kNm V1=96.28kN V2=96.28kN	- M1=345.1kNm M2=382.7kNm V1=135.0kN V2=135.0kN	- M1=454.6kNm M2=156.3kNm V1=264.9kN V2=264.9kN
PACMSW	Ax= -24.90kN M1=1168kNm M2=978.7kNm V1=320.3kN V2=320.3kN	Ax= -246.4kN M1=2661.0kNm M2=2712.0kNm V1=768.9kN V2=768.9kN	Ax= 302.4kN M1=673.5kNm M2=1402.0kNm V1=186.7kN V2=186.7kN	- M1=816.4kNm M2=765.3kNm V1=331.8kN V2=331.8kN	- M1=1290.0kNm M2=243.6kNm V1=787.4kN V2=787.4kN

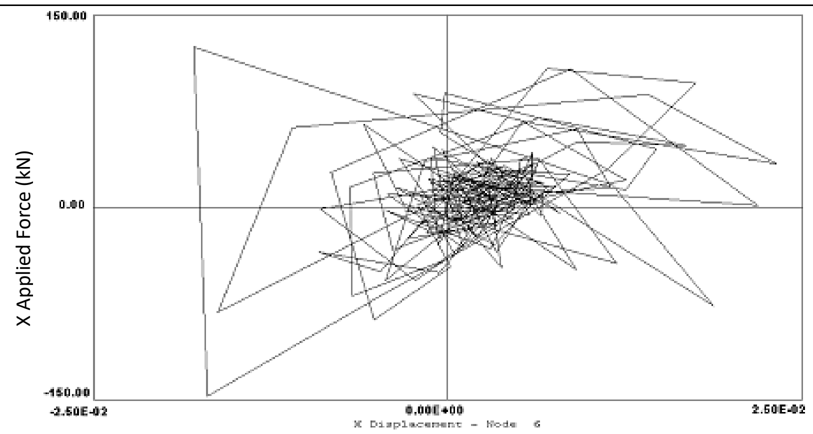
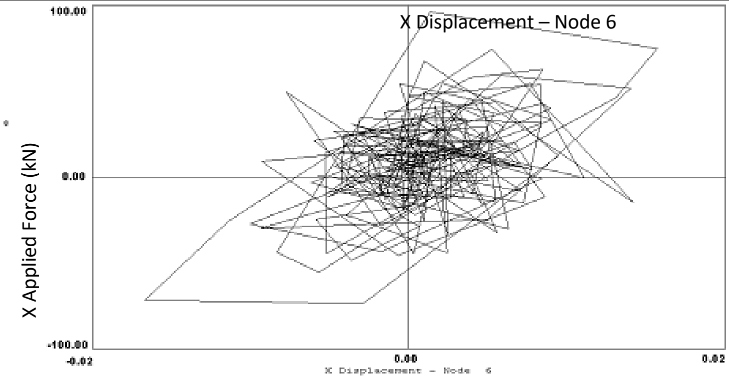
D. HYSTERESIS LOOPS

Table 8 shows the comparison of hysteresis for Node 6. Maximum applied force to push the structure and to pull the structure for each of the chosen earthquake events, ranked from highest to lowest force is:

- PACMSW 310.0 kN push and 397.0 kN to pull
- EL40NSC 110.0 kN push and 88.0 kN to pull
- EL40EWC 97.0 kN push and 72.0 kN to pull

The percentage differences of maximum applied forces are 13.4% and 219.5% higher under EL40NSC and PACMSW against the lowest EL40EWS.

Table 8: Hysteresis loop at Node 6

Earthquakes	Node 6
EL40NSC	
EL40EWC	 X Displacement – Node 6

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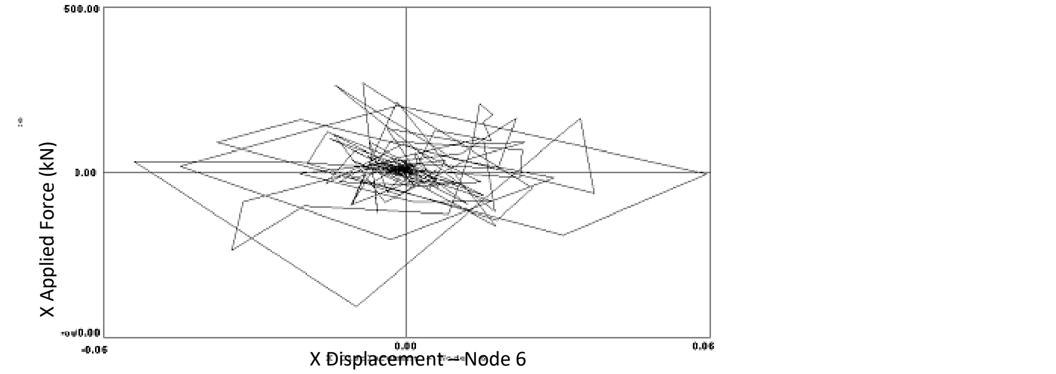
PACMSW	

VII. DISCUSSION

The prototype of RC turbine foundation has been successfully modelled using RUAUMOKO 2D program and run under Imperial Valley earthquake records and San Fernando earthquake records. The program has several choices of modelling approach and for this study it was appropriate to base the analysis on non-linear dynamic theory, using time-history analysis. Seismic performances of the RC turbine foundation under the three chosen earthquake excitation records have been compared. Mode shape, natural period and natural frequency are determined, followed by nodal displacement and positional drift of the turbine foundation. The response spectrum of the three chosen earthquakes has been plotted using DYNAPLOT and evaluated for the RC turbine foundation. Based on the modelling results, the turbine foundation under Imperial Valley earthquakes does not exceed yield drift and remains in the elastic condition throughout the earthquake events. The RC turbine foundation is safe and is able to carry gravity loading as designed using BS 8110 [6]. However, under the typical cyclical loading imposed by excitation from San Fernando earthquake record, nodal drift has exceeded the yield drift limit, with the greatest excess displacement defects occurring in columns. Therefore, the turbine foundation will not be safe and collapse is predicted by the modelling using Ruaumoko programme.

VIII. CONCLUSION

The following conclusion had been drawn based on this study:

1) The prototype of RC turbine foundation has been successfully modelled using RUAUMOKO 2D program using Imperial Valley Earthquake and San Fernando Earthquake past records based on non-linear dynamic theory, using time-history analysis.
2) Seismic performances of RC turbine foundation were compared under these three earthquake records and the San Fernando Earthquake shows the maximum nodal lateral displacement, maximum member forces and maximum moments of beam-column joints for RC turbine frame.
3) Based on the modelling results, the RC turbine frame subjected to Imperial Valley Earthquakes does not exceed yield drift and remains in the elastic condition and this frame is safe under this earthquake attack and it also able to carry the gravity loading which has been designed using BS 8110.
4) However, the RC turbine frame subjected to San Fernando Earthquake has exceeded the yield drift limit and the maximum nodal displacement is marked as red colour in Ruaumoko 2D program. Therefore, this RC turbine frame will not safe under this earthquake attack and it is predicted that the frame will collapse and experience severe damages.

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Nor Hayati Abdul Hamid was born at Selangor, Malaysia in 1966. She obtained her BSc in Civil Engineering from U.S.A and MSc. in Structural and Management from United Kingdom. She completed her PhD (Earthquake Engineering) from University of Canterbury, Christchurch, New Zealand in 2007. She has been working as a lecturer at University Teknologi Mara, Shah Alam, Selangor for 21 years.

Her research interests are seismic performance of precast buildings under earthquake excitation, Damage Avoidance Design, Direct Displacement Based Design, design of rocking precast hollow core walls under earthquakes, wall-slab connection, precast beam-column joints, tunnel form system using Industrialized Building System, fragility curves and Incremental Dynamic Analysis.

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