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Research paper

Damage states of nine-story tunnel form building under earthquake excitations using Ruaumoko 2D program

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Abstract

A lot of structural damage was observed after the earthquakes and it is very important to determine the level of safety of these buildings. One of the popular construction methods in Malaysia is a tunnel form building system which built for apartments, condominiums and residential houses using British Standard known as BS 8110. This standard is the non-seismic code of practice. Subsequently, a prototype four bay nine-story tunnel form building system was designed using STAAD PRO program and modeling using Ruaumoko 2D program under seven past ground motion records. The nonlinear time history analysis and parameters of dynamic analysis were obtained from this program. The earthquake excitations, spectral displacements, pseudo spectral accelerations, mode shapes and maximum deformations were used to determine the level of safety for this type of building. The comparison was made between the experimental results and modeling results in order to assess the levels of safety for seven past ground motions. It can be concluded that this building survives under Bukit Tinggi Earthquake and Greece Earthquake, severe damage under EL-Centro North South Earthquake and Pacoima Dam Earthquake and collapse under the 1940EL-Centro East West Earthquake, Norway Earthquake and the 1985 Mexico City Earthquake.

Keywords: *Spectral Acceleration; Level of Safety; Earthquake Excitations; Survive; Collapse.*

1. Introduction

The damages states of reinforced concrete buildings can be classified based on the visual observation at site or experimental work which conducted in the laboratory. In order to get a clear picture on the visual observation damages, percentage drift or lateral displacement and ductility, it is recommended to test the specimen in the laboratory under quasi-static in-plane lateral cyclic loading. The damage states can be developed on the basis of cost-ratio link with peak ground acceleration, structural and non-structural damages which useful for estimating economic losses. Whitman [1] who developed damage states based on damage cost data from the 1971 San Fernando Earthquake. Meanwhile, the seismic loss estimation should include well-defined damage descriptions, physical parameters relating observed damage to structural response, repairs and cost ratios according to the building type being investigated. It must have a scoring system, provide rational and unbiased method for ranking damage scales which used to identify loss estimation weakness and improvements [2]. In addition, ATC-13 [3] used expert opinion to predict the losses from earthquakes and provided a wide range of classification damages states for safety evaluation of damaged buildings. Furthermore, HAZUS [4] used predefined set of cost ratios for buildings to forecast the damage and loss in buildings due to future earthquakes. In contrast, FEMA 273 [5] provided damage states based on the expected seismic performance of the building’s safety and serviceability after an earthquake.

Nowadays, a lot of earthquakes occur around the world not only limited within “Pacific Ring of Fire” but also happened quite far away from the boundaries of tectonic plates. For example, West Malaysia is located 500 km from Sumatran fault and East Malaysia has a few active faults [6]. There exist at least two active fault zones between Ranau and Mount Kinabalu which are Mensaban Fault and Lobou-Lobou Fault. These faults run generally in the west-north-west to east-south-east direction and it is 12 km wide over a distance of 110 km from Tuaran towards east and into the interior of Sabah [7]. On the other part of the world such as Afghanistan is a land-locked mountainous country which located within South Asia. Afghanistan comprises of four major active fault lines namely Chaman Fault, Hari Rud Fault, Central Badakhshan Fault and Darvaz Fault, which pass through the middle part of this country [8]. Most of the buildings and houses in Afghanistan were constructed using poor quality of materials such as rubble stone, masonry, mild, uncooked and cooked brick. Whereas, most of the RC concrete structures were designed using Russian National Standards; SN 460-74 [9] where there is no provision for the earthquakes. The safety of these buildings and houses still questionable until research is conducted to verify their level of safety. Therefore, the aim of this paper is to determine the level of safety for tunnel form building which commonly built in Malaysia using damages states and Ruaumoko 2D program under six near field past earthquake records and one far field earthquake excitations.

The damage states seismic assessment based on the experimental work to produce a fragility curve by incorporating HAZUS [4] and FEMA [5] had been conducted for precast beam-column joint with

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corbel [10], precast shear key wall panel [11] and reinforced concrete structures [12]. Many researchers had validated the experimental hysteresis loops with modeling hysteresis loops using Ruaumoko 2D to get good agreement and correlation between them [13-18]. Most of them obtained a similar pattern of hysteresis loops between experimental and modeling using the HYSTERES folder in Ruaumoko 2D program. After validating the hysteresis loops, the parameters that obtained from modeling will be used to model four bay nine-story tunnel form building under several past ground motions. The modeling results will be used to determine the level of safety for this type of building based on visual observation of damages obtained from experimental work [19]. The details of the research methodology of this study are described in the following section.

2. Research methodology

In this study, four bay nine-story tunnel form building is chosen as a prototype building with overall dimension of 27x24x15m with inter-story height of 3m for each floor. The rigid RC shear wall and floor slab are 200mm thick. This prototype building was designed in accordance to BS8110 without considering the seismic loads using STAAD PRO program. Figure 1 shows an isometric view of the four bays, nine-story tunnel form building which had been designed using STAAD PRO program. The detailing of reinforcement for the walls and slabs of tunnel form building will be used as data input for Finite Element Modeling (FEM) for Ruaumoko 2D program. Figure 2 shows a total number of 45 nodes for the shear wall and 36 elements for the floor slabs. Subsequently, the prototype four bay nine-story was run under seven past earthquake records as a rigid RC building in the monolithic connection system together with shear wall. The selection of earthquakes for nonlinear time history analysis depending on the peak ground acceleration location at site, database available and scaling ground motions. A total number of 40 ground motions were selected using each of the methods for measuring bias in structural response [21], [22], 10 ground motions for two bay three-story tunnel form building [19], 7 ground motions for two-story precast school building [20] and 20 ground motions for single-story warehouse using precast hollow core wall [23]. Hence, 7 numbers of ground motions were selected to run for four bays, nine-story tunnel form building obtained from the database in Quake Folder in Ruaumoko 2D program [24]. The Quake Folder consists of the control parameters such as peak ground acceleration, duration of the earthquake, time history analysis and location of the earthquake.

The earthquake excitations format for this folder are in the extension of CALTEC, EQC, BERG, EQB, FREE and EQF. Table 1 shows the characteristics of the seven selected past earthquakes such as format earthquake record, the magnitude of the earthquake, classification of earthquake, peak ground acceleration, focus depth, location and year of occurrence these earthquakes.

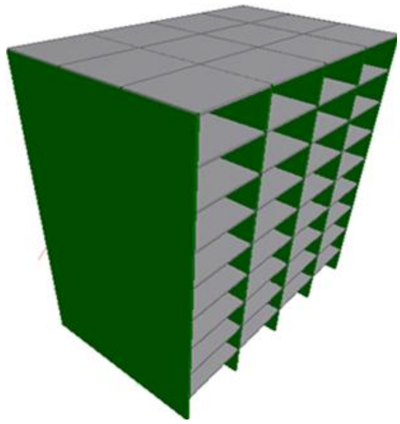


Fig. 1: Isometric View of Four Bay Nine-Story Tunnel Form Building Using STAAD PRO Program.

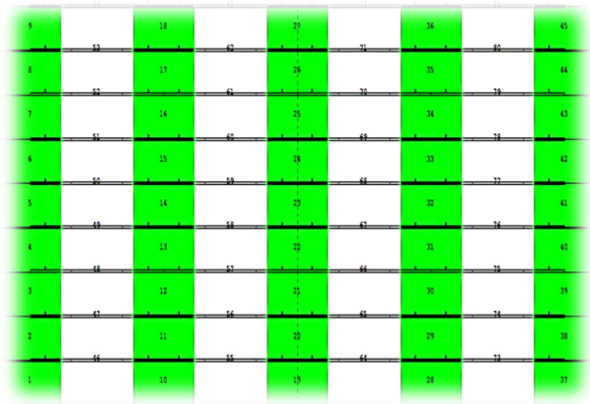


Fig. 2: Number of Nodes and Elements for Four Bay Nine-Story Tunnel Form Building Using Ruaumoko 2D Program.

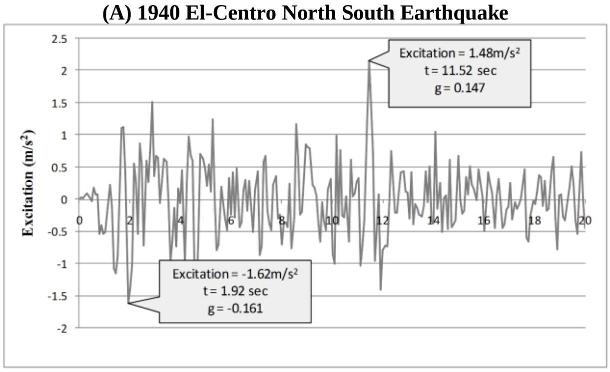
Table 1: Characteristics of Seven Selected Past Earthquake Records

Format of Earthquake Record	Magnitude (Richter Scale)	Classification of Earthquake	PGA (g)	Depth (km)	Location	Year
MEXSCT1L.EQC	8.1	Great	1.230	16	Mexico City	1985
NORWAY.EQC	6.2	Strong	0.615	10	Svalbard	2008
EL40NSC.EQB	7.1	Major	0.338	6	El Centro North South	1940
GRACE.EQF	6.0	Strong	0.615	10	Athens, Greece	1999
PACMSW.EQB	6.6	Strong	1.190	8.4	Pacoima Dam	1971
EL40EWC.EQB	5.5	Moderate	0.214	6	El Centro East West	1940
BUKITTINGGI.EQF	3.0	Minor	0.000464	3	Bukit Tinggi, Pahang	2007

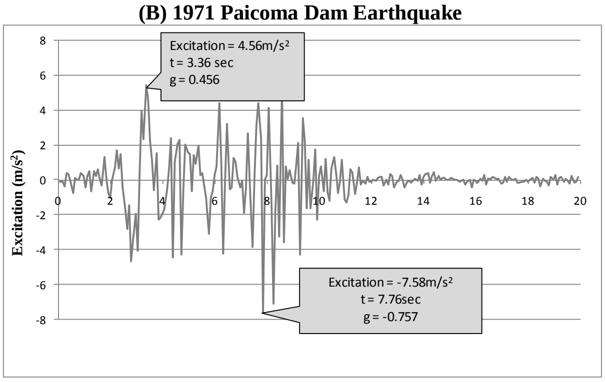
3. Analysis and results

The selection of the past earthquakes based on its classification together with magnitude Richter scale such as great (bigger than 8), major (7 to 7.9), strong (6 to 6.9), moderate (5 to 5.9) and minor (lower than 3.0) as shown in Table 1. Some examples of the graphs (earthquake excitation versus time) for the 1940 EL40-Centro North South, the 1971 Pacoima Dam is 0.48m and the 2007 Bukit Tinggi Earthquake records as shown in Figure 3.

(A) 1940 El-Centro North South Earthquake



(B) 1971 Paicoma Dam Earthquake



(C) 2007 Bukit Tinggi Earthquake

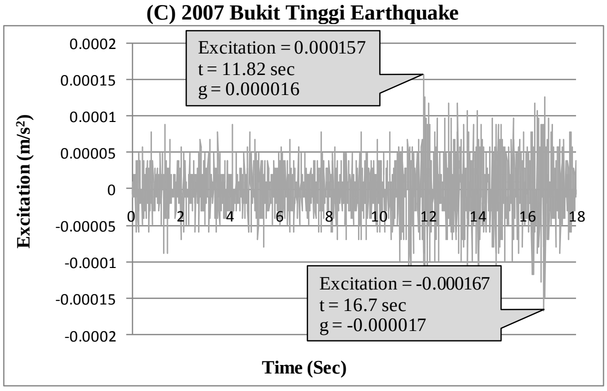


Fig. 3: Earthquake Excitations.

The equation of motion for SDOF by incorporating the ground motion force can be expressed in Equation 1

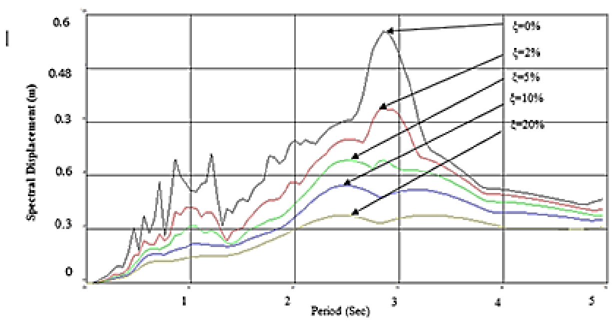
$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_g(t) \qquad (1)$$

Where $\ddot{x}_g(t)$ is acceleration due to ground motion. The lateral displacement as a function of time, x(t) can be solved using the Second Order Differential Equation under general solution and Duhamel's Integral as derived in Equation 2.

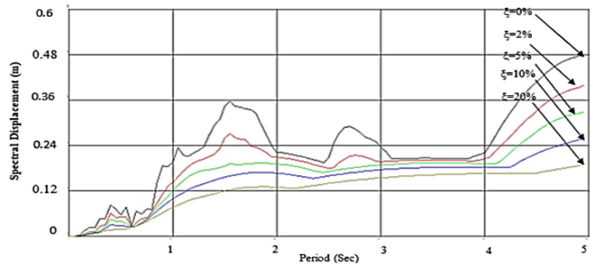
$$x(t) = \int_0^t \ddot{x}_g(\tau)\frac{e^{-\varepsilon\omega_d(t-\tau)}}{\omega_d}\sin\omega_d(t-\tau)d\tau \qquad (2)$$

The spectral displacement of earthquake versus time can be plotted using Equation 2. Figure 4 shows the graph of spectral displacement versus time for the 1940 EL40-Centro North South, the 1971 Pacoima Dam is 0.48m and the 2007 Bukit Tinggi earthquake records with various percentages of damping after plotting using DYNAPLOT program in Ruaumoko 2D. It can be observed that the structure without dumping (ξ=0.0%) has the biggest displacement as compared to the structure with mechanical damper or base isolation system. The maximum spectral displacement at 0.0% damping for 1940 EL40-Centro North South is 0.567m, the 1971 Pacoima Dam is 0.48m and the 2007 Bukit Tinggi is 0.00000335m.

(A) 1940 EL40-Centro North South Earthquake



(B) 1971 Pacoima Dam Earthquake



(C) 2007 Bukit Tinggi Earthquake

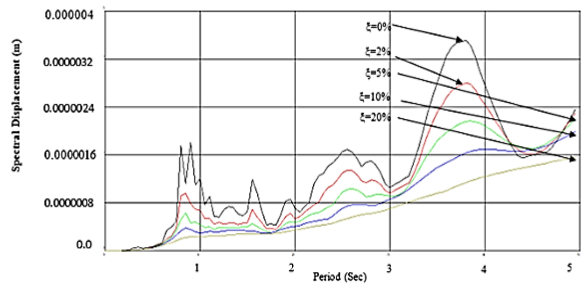


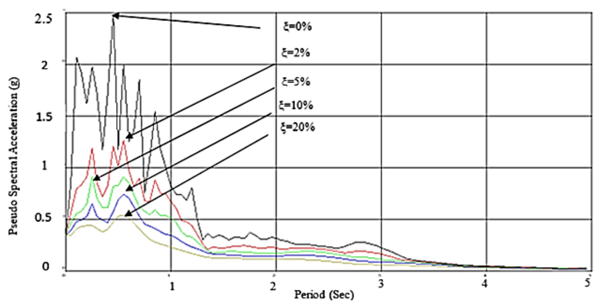
Fig. 4: Graphs of Spectral Displacement Earthquake Versus Time.

The pseudo spectral acceleration (PSA) versus time can be plotted using Equation 3 for each of seven earthquakes.

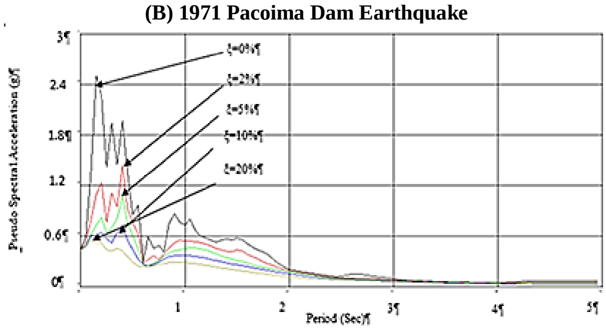
$$\ddot{x}_g(t) = \omega_n^2 x(t) \text{ where } \omega_n = \sqrt{\frac{k}{m}} \qquad (3)$$

Figure 5 shows the graph of pseudo spectral acceleration (PSA) versus time for 0%, 2%, 5%, 10% and 20% damping using Ruaumoko 2D program. It can be observed that the structure without damper has the highest pseudo spectral acceleration as compared to the structure with the mechanical energy dissipaters or base isolation system. The maximum pseudo spectral acceleration at 0.0% damping for the 1940 EL40-Centro North South Earthquake is 2.4m/s^2, the 1971 Pacoima Dam Earthquake is 2.46m/s^2 and the 2007 Bukit Tinggi is 0.00000021m/s^2.

(A) 1940 EL-Centro North South Earthquake



(B) 1971 Pacoima Dam Earthquake



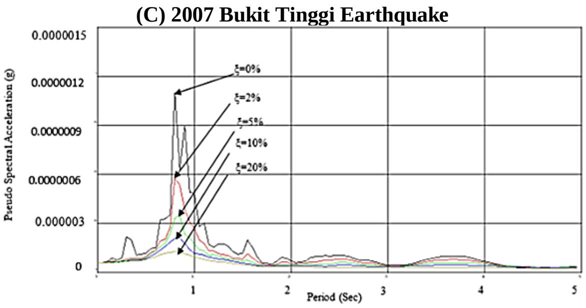


Fig. 5: Graphs of Pseudo Spectral Acceleration Versus Time.

Subsequently, the mode shapes for nine-story tunnel form building as shown in Figure 2 can be determined under seven past earthquake records. Figure 6 presents all the nine mode shapes of a tunnel form building which obtained from the DYNAPLOT Program. The analysis and results of nine-story tunnel form building, the maximum lateral displacements were recorded at nodes 9, 18, 27, 36 and 45 which were located at the top level of this building. All the nine mode shapes were represented the deflected shapes of prototype tunnel form building in three directions which are X-axis, Y-axis and Z rotation. The maximum deflection of tunnel form building was found to occur in mode shape eight at node 45 with 1m in x-axis, $6.5x10^{-4}$m in y-axis and 0.171m in the z-rotation. The minimum lateral displacement was recorded in mode shape one at node 27 where the values of $-6.9x10^{-6}$m for x-axis, $-6.6x10^{-8}$m in y-axis and $6.7x10^{-7}$ m in z rotation.

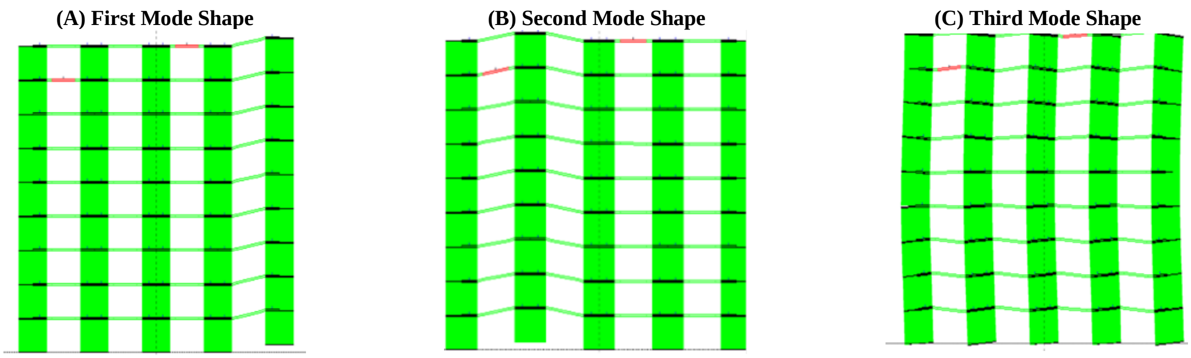
Table 2 shows the maximum lateral displacement at the top of the prototype nine-story tunnel form building under seven earthquake records. Generally, it can be concluded that as the peak ground acceleration increases, the lateral displacement or drift also increases. The drift of the structure can be found by dividing the maximum lateral displacement over the effective height of the building multiplied by 100%. According to the analysis of results, it can be seen that the maximum lateral displacement was occurring at the 1986 Mexico City earthquake in 1.633m with 6.05% drift at positive envelope and -1.184m or -4.39% drift in negative envelope. From the animation of the vibration of the building in Ruaumoko 2D program, the full collapse mechanism occurred under this earthquake.

However, the minimum lateral displacement was occurring under the 2007 Bukit Tinggi earthquake in 1.035x10-3m or +0.0038% drift in positive envelope and -1.041x10-3m or -0.0038% drift. According to Kay Dora [15] when the inner storey drift exceeds from the 2% and 2.5% the structure cannot be safe under lateral load and will suffer severe and partial damages. Therefore, the tunnel form building only will not experience structural damage under the 2007 Bukit Tinggi Earthquake.

Table 2: Maximum Lateral Displacement for Seven Past Earthquake Excitations

Earth Quakes	Peak Ground Acceleration (g)	Positive envelope Displacement(m)	Negative envelope Displacement(m)	Percentage Drift (%) Pushing	Pulling
MEXICO	1.230	1.633	-1.184	+6.05%	-4.39%
NORWAY	0.615	1.096	-1.162	+4.05%	-4.30%
EL40NSC	0.348	0.3224	-0.2609	+1.19%	-0.96 %
GREECE	0.615	0.23	-0.193	+0.85 %	-0.72 %
PACOIMA DAM	1.190	0.355	-0.489	+1.31%	-1.81%
EL40EWC	0.214	0.52	-0.3023	+1.93 %	-1.12 %
BUKIT TINGGI	0.000464	$1.035x10^{-3}$	$-1.041x10^{-3}$	+0.0038%	-0.0038%

Hitherto, there are many research works had been conducted on tunnel form building system regarding about experimental work and modeling. The seismic performance evaluation of two and five story tunnel form building based on the nonlinear pushover analyses for 2D and 3D model [25]. The estimation of fundamental periods and dynamic properties of shear-wall dominant between 2 to 15 story tunnel form buildings with 40 plan configurations had been studied [26]. A new formula for explicit determination of their fundamental period is developed in addition to a recommended response reduction factor and reinforcement detailing around shear-wall openings [27]. Afterward, the strengths and weaknesses of tunnel form buildings were addressed in terms of design considerations and construction applications [28]. Later, experimental investigations of the inelastic seismic behavior of tunnel form buildings (box-type) were performed [29]. Another experimental study had been conducted to decrease the uncertainty of linear and nonlinear behaviour of one-fifth three-story tunnel form building [30]. Lately, a series of experimental work has been performed and compare the seismic performance of repairing and unrepaired of tunnel form building using steel plate, steel angle, Carbon Fiber Reinforced Polymer and additional shear wall [19]. Thus, the objective of this paper is to determine the level of safety for tunnel form building under seven past earthquake records using Ruaumoko 2D program.



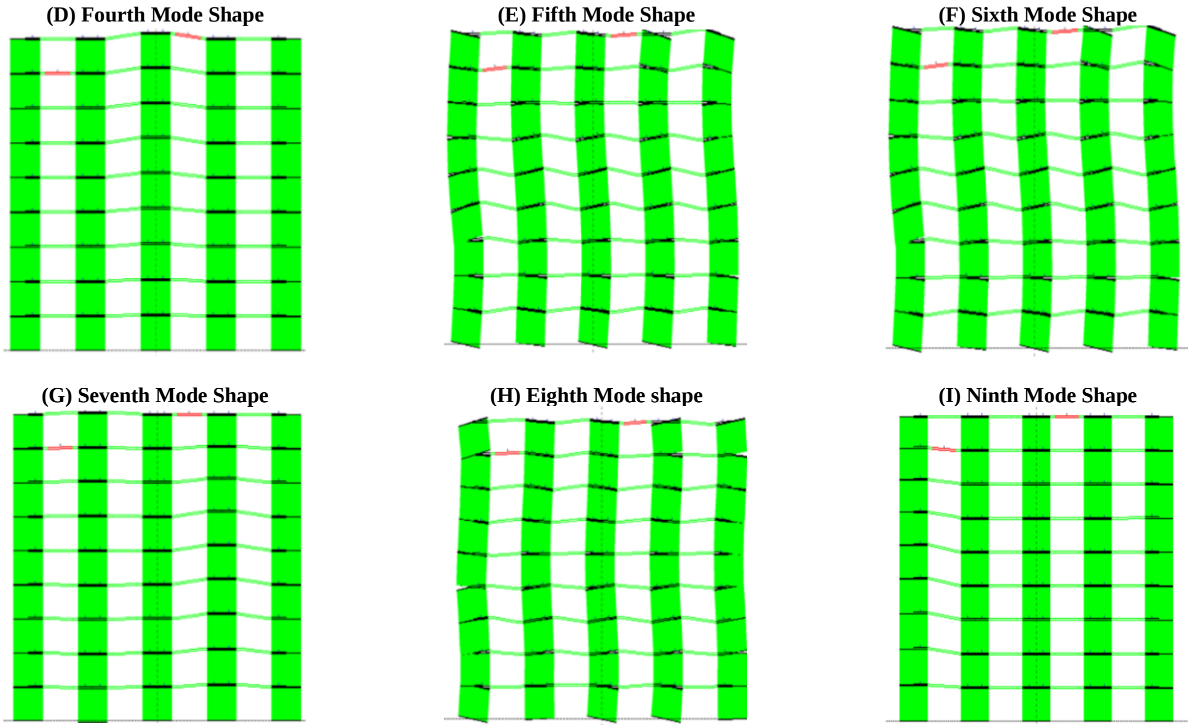


Fig. 6: Nine Mode Shape for Nine-Story Tunnel Form Building Under Seven Earthquake Excitations.

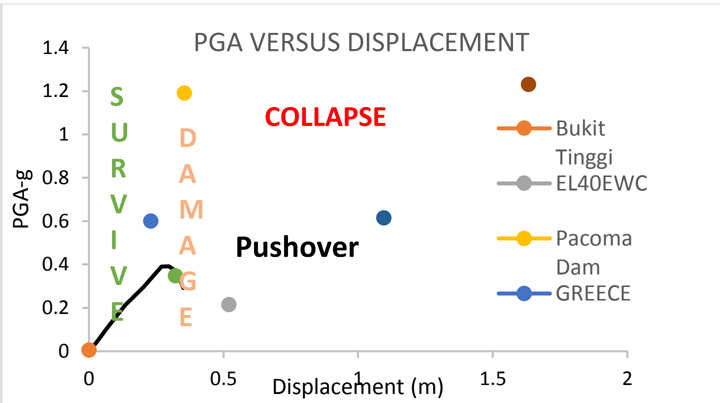


Fig. 7: Level of Safety Under Seven Past Earthquake Records.

Previously, it is very important to determine the level of safety for nine-story tunnel form building by comparing the output results from Ruaumoko 2D and static pushover analysis based on the experimental work conducted by Anuar [19]. The static pushover analysis of experimental work can be determined using Equation 4, 5, 6 and 7.

$$C_d = \frac{SA}{TB_L} \text{ and } C_c = \frac{F}{W} \quad (4)$$

$$T = 2\pi\sqrt{\frac{m}{k}} = 2\pi\sqrt{\frac{W\Delta}{Fg}} = 2\pi\sqrt{\frac{\Delta}{C_c g}} \quad (5)$$

The performance point occurred when the demand curve meets the pushover analysis where $C_d = C_c$ and by squaring both sides, it becomes as in Equation 6.

$$C_d^2 = C_c^2 = \left(\frac{SA}{2\pi B_L \sqrt{\frac{\Delta}{C_c g}}} \right)^2 \quad (6)$$

Therefore, the spectral acceleration for the experimental work can be derived in Equation 7.

$$(SA)_i = 2\pi B_L \sqrt{\frac{\theta H C_C}{g}} \text{ where } \Delta = \theta H \quad (7)$$

Figure 7 shows the level of safety for nine-story tunnel form building by comparing the experimental data [19] and output results from Ruaumoko 2D. The graph of spectral acceleration or also known as peak ground acceleration versus displacement was plotted as shown in Figure 6. It can be seen that nine-story tunnel form building will survive under the 2007 Bukit Tinggi Earthquake and Greece Earthquake which behave elastically under pushover analysis. Moreover, this type of building will behave nonlinearly for the 1940 EL-Centro North South Earthquake and Pacoima Dam Earthquake with substantial damage such as spalling of concrete and buckling of the reinforcement bars in the wall panel. The tunnel form building will suffer a partial collapse or full collapse under the 1940EL-Centro East West Earthquake, Norway Earthquake and the 1985 Mexico City Earthquake.

4. Conclusions

The four bay nine-story tunnel form building was designed successfully according to the BS8110 which is non-seismic code practice under gravity loadings using STAAD PRO V8i program. The Ruaumoko 2D program was fully utilized to determine the non-linear dynamic analysis of the building under seven selected earthquake excitations. The results from the output file were analyzed in order to determine the dynamic parameters such as spectral displacement, pseudo spectral acceleration, mode shapes, maximum lateral displacement for the positive and negative envelopes. There is a total number of nine mode shapes and mode shape 8 was found to be the worst mode shape with 1633mm. The maximum lateral displacement of the building was also determined for the 1986 Mexico City with 1633mm. Finally, the graph of spectral acceleration versus displacement was plotted by comparing the pushover analysis curve (capacity curve) which was determined from experimental work and seven past earthquake excitations (demand curve). It can be concluded that four bay nine-story tunnel form building survives under the 2007 Bukit Tinggi Earthquake and Greece Earthquake. The 1940 EL-Centro North South Earthquake and Pacoima Dam Earthquake have severe damage and collapse under the 1940EL-Centro East West Earthquake, Norway Earthquake and the 1985 Mexico City Earthquake.

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