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Seismic Performance of Three Ancient Stupas in Anuradhapura, Sri Lanka

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Abstract: Ruwanweli, Abayagiri and Jetavana stupas situated in Anuradhapura, are three ancient wonders of Sri Lanka. Renovations and restorations of these stupas were started in early parts in the 20th century and carried out until recently. Considering their geometric proportions, cultural and social importance, there is an impending need to assess these stupas for seismic performance to avert any possible damages due to seismic activities that might occur in the future. Further, this requirement has become more important due to some researchers' predictions on intraplate activities in the behaviour of ancient stupas with respect to possible earthquake accelerations. In this regard, two-dimensional numerical models of the three stupas were prepared using SAP2000 v.14: general-purpose software package. Both static and dynamic analyses were performed on numerical models for self-weight and two recorded acceleration histories, respectively. Two acceleration histories are from Mahakandarawa, Sri Lanka and Manjil, Iran. Material parameters of ancient bricks were obtained from previous literature works and experimental test results conducted on similar bricks of another ancient stupa in Sri Lanka. Considering the past records of earthquakes that have occurred in Sri Lanka, it was understood that all three stupas are in the safe realm under magnitude 4.7 earthquakes (Peak Ground Acceleration of 5.48×10^{-5} g). Even referring to the stress distribution with magnitude 7.4 Manjil earthquake (Peak Ground Acceleration of 0.4 g), both Ruwanweli and Jetavana stupas are in safe zone.

Keywords: Stupa, Ancient bricks, Earthquake, Numerical model, Seismic performance

1. Introduction

1.1 Preliminaries

Ancient stupas of Sri Lanka are considered to be engineering marvels of the ancient world. Construction of stupas began in the 3rd Century BC and reached its zenith by the 3rd Century AD with the construction of the Jetavana stupa which is still the overall (including foundation) tallest brick structure in the world. There are about thousands of stupas in Sri Lanka and some of these stupas are gigantic in dimensions [9]. The shapes of stupas are categorized into six types but only bubble and paddy-heap shapes are the most common shapes of large stupas in Sri Lanka [7].

Analysis of these ancient stupas for restoration purposes has been carried out by a few researchers in the past [3, 8, 10, 11, 12 & 13]. However, the seismic performance of ancient stupas has not been addressed according to the available literature. Even though Sri Lanka is not located near any of the plate boundaries which tend to create an earthquake, it is located on the plate that extends from Australia to India. Some scientists believe that there is a tendency for a new plate boundary to form across the Southern Indian Ocean approximately 1000 km from the south coast of Sri Lanka [5].

Further, the intra-plate activities on the northwest to southwest coasts of Sri Lanka are not considered significant up to now. During the exploratory drilling for oil in Cauvery and Mannar basins, frozen basaltic lava flows have been encountered. As they are interlayered with sediments, it could be postulated that the rift zone was seismically active in the past. Seismic exploration of the sedimentary

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succession in the Cauvery and Mannar basins has indicated the relative disposition of faulted blocks of rocks on the basin floor. Sedimentary deposits increase reactivation potential of the fault zone by facilitating relative motion between already faulted blocks of rocks, leading to higher seismicity potential.

Though highly activated seismic zones are quite far away from Sri Lanka, the potential of the above sedimentary basins to the northwest and southwest of Sri Lanka becoming foci of future moderate magnitude earthquakes has a certain probability [14].

From the point of material science, clay brick material is brittle and does not have sufficient tensile strength to absorb the energy generated due to seismic activities. Earthquakes have had devastating effects on masonry structures in the recent past in other areas of the world. For example, a powerful 7.8 magnitude earthquake struck Nepal on the 25th April 2015 as the result of faulting on or near the main frontal thrust between the Indian plate and the overriding Eurasia plate to the north. Many ancient monuments in Nepal were demolished by this earthquake and aftershocks. Further, the 6.8 magnitude Bagan earthquake of Myanmar in 2016 devastated many masonry structures in the ancient city of Bagan. The 6.6 magnitude Bam earthquake of Iran left many collapsed masonry structures in 2004. Therefore, it is apparent that masonry structures are highly vulnerable to seismic activities.

Considering these facts, a study on the effects of potential seismic activities on these ancient stupas in Sri Lanka is important, considering their continued safety. As such, the main aim of this paper is to analyse three significant ancient stupas located in Anuradhapura for possible earthquake scenarios. In order to achieve the aim, the following objectives were focused in this study:

i. Preliminary data collection;
ii. Static and dynamic analysis with two-dimensional (2D) numerical models of the three stupas; and
iii. Assessment for the seismic vulnerability of stupas under most critical results leading to vulnerability.

2. Three Stupas in Anuradhapura

Ruwanweli stupa was built by King Dutu Gemunu (161 – 137 BC) and it is also known as "Mahathupa" since at the time it was built, there was no stupa in the world that matched its size. Restoration of Ruwanweli stupa was done in the 1930s by religious organizations and there was little involvement from the Department of Archaeology. Therefore, less data is available regarding the renovation work that took place those days.

Abayagiri stupa was built by King Walagamba (89-77BC) and it is the second-largest stupa in Sri Lanka. From the practice obtained from restoration and conservation works on Mirisawetiya and Jetavana stupas, conservation works on the Abayagiri stupa commenced around 1996. Although in the beginning it was suggested to restore as Mirisawetiya stupa type restoration, later it was agreed to conserve as Jetavana stupa conservation.

Jetavana stupa is located eastward of the Abhaya Wewa and it was built by King Mahasen (275 -301 AD). The original height of the stupa was estimated as 123m which would have made it the third tallest building in the world (excluding the height of the foundation) at the time it was built. Further, it is still the largest brick structure in the world even after thirteen centuries of its construction.

2.1 Geometric Details of Stupas

All three stupas under consideration are solid masonry structures composed of burned clay bricks of different sizes. The present geometric details of the three stupas are given in Table 1.

Table 1 - Present Geometric Details of the Three Stupas in Anuradhapura [10]

Name of the Stupa	Dome Shape	Present Height from Platform (m)	Dome Diameter at Platform (m)
Ruwanweli	Bubble	91.4	90.8
Abayagiri	Paddy- heap	73.0	99.1
Jetavana	Paddy- heap	70.7	102.0

As shown in Table 1, the present height of the Ruwanweli stupa is higher than that of the Jetavana stupa and this fact is due to the restoration work of the two stupas carried out in the 20th century.

Table 2 shows the mechanical properties of bricks in Jetavana stupa. It also illustrates the mechanical properties of the Sandagiri stupa which has the highest mechanical properties of all ancient stupas which have been assessed up to now. It also shows the mechanical properties of modern bricks. It is apparent from Table 2, that most of the mechanical properties of bricks used in the Jetavana stupa have higher values than those of modern bricks.

Table 2 - Mechanical Properties of Ancient & Modern Bricks [11]

Source	Density (kg/m^3)	Young's Modulus (GPa)	Poisson Ratio	Compressive Strength (MPa)	Tensile Strength (MPa)
Sandagiri stupa	1840	9.79	0.27	11.60	1.54
Jetavana stupa	1723	4.50	0.25	8.50	0.85
Modern Bricks	1768	1.92	0.21	5.30	0.55

The mortar used for ancient brickwork in stupas is a clay slurry type called "Butter clay" with an adhesive from a tree and a solvent of sweetened water. This mortar was used in very thin layers, unlike modern cement sand mortar [6]. Analysis of brick mortar in Abayagiri stupa revealed that it consisted of finely crushed dolomite lime mixed with 1:4 in sand:clay whereas Jetavana stupa revealed it to be 1:5 [1]. This fact concludes not only the size and strength of ancient bricks but the clay mortar ratio has also been changed with time [2].

2.2 Historical Records of Earthquakes in Sri Lanka

The earliest chronicle of an earthquake in Sri Lanka had been recorded as on the 14th April 1615 near Colombo. The epicenter of the earthquake cannot be identified due to a lack of data. According to the reported damage to the properties, it had been estimated to be around magnitude 6.5 earthquake. From 1615 to 1800 there are no records of an earthquake near Sri Lanka. An earthquake had been reported in 1823 from the northern Indian ocean and in 1900 from Coimbatore - Neelagiri hills.

There are some newspaper records of earthquakes in 1882, 1924, 1938 and 1944. A Milne seismograph was established in the Colombo observatory in 1909. The observation from this station was connected to the global network that includes 350 stations. Records of this seismograph were published in the Annual report of Colombo observatory and international Seismological summary, University Observatory, Oxford. However, at present this seismograph is not functioning. Three seismometers were installed by the Geological Survey and Mines Bureau (GSMB) in 1992, namely, at Pallekelle, Hakmana and Galkulama. Peak Ground Acceleration values are now available from the locations of these three seismometers. Out of all recorded earthquakes in Sri Lanka, the one that recorded in Mahakanadawa on the 19th November 2011, has the highest magnitude.

3. Methodology

3.1 Preliminary Data Collection

Preliminary data collection was done to construct 2D numerical models and to perform static and dynamic analyses. For the above requirement, following data were collected.

- Geometric data of stupas such as base diameter, height of the dome, height and length of the square chamber.
- Age of each stupa and material used to construct these stupas in ancient times.
- Material and methods used for renovation and restoration of stupas.
- Acceleration-time data of earthquakes in Sri Lanka from Geological Surveying and Mines Bureau.
- Acceleration-time data of earthquakes in other countries.

3.2 Experimental Testing of Ancient Bricks

Material properties of ancient stupas were obtained from previous studies [11]. It was observed that the size and material properties of ancient bricks changed with time. Therefore, it was necessary to find out the material properties of ancient bricks in other stupas as well. Collecting ancient bricks from Abayagiri, or Ruwanweli stupas were not possible as all stupas are already renovated or restored. However, it was noted that the Digavapi stupa was constructed in the same time period (2nd to 1st century BC) and the stupa is under renovation at present. Therefore, ancient brick samples taken from Digavapi stupa were used for testing. These experiments were intended to evaluate the properties of ancient bricks such as elastic modulus, compressive strength, specific gravity and moisture content.

3.3 Earthquake Acceleration Data

There are three acceleration-time files such as horizontal East-West direction, horizontal North-South direction and vertical direction. Up and down direction earthquake acceleration data was collected to perform dynamic analysis of stupas since those data gives maximum seismic vulnerability of stupas. In this context, two acceleration histories were used and their summaries are given in Table 3. As first, the highest magnitude of an earthquake recorded in Sri Lanka was selected for the analysis, and it has the peak ground acceleration of 5.48×10^{-5}g.

The selection of the highest magnitude of acceleration data from Sri Lankan context would give researchers to understand performance of stupas under Sri Lankan context. Further, it is also important to gain the understanding of the performance of stupas under higher magnitude of earthquake than those of Sri Lanka. In line with this requirement, the magnitude 7.4 Manjil, Iran earthquake was selected to find the effect of a higher magnitude earthquake on the ancient stupas. Manjil earthquake is one of the worst earthquakes to hit Iran and it would provide a kind of worst case scenario for the seismic performance on stupas. It has a peak ground acceleration of 0.4 g.

Table 3 – Earthquake data for dynamic analysis

Location	Date	Magnitude	Time interval (s)	Number of time steps
Mahakanadarawa, Sri Lanka	2011/11/19	4.7	20	4810
Manjil, Iran	1990/06/21	7.4	0.02	2671

3.4 Two Dimensional Numerical Modelling of Stupas

Considering Ruwanweli stupa, geometry and boundary conditions are symmetric about the vertical axis. For static analysis, only self-weight is applied with no other significant dead or imposed loads. Therefore, the static analysis involves with an axisymmetric problem. In line with above consideration, static analysis of Ruwanweli stupa is performed as a 2D analysis involving with section properties as plane stress "Asolid" elements. Considering Abayagiri and Jetawana stupas, dome geometries are not exactly symmetric due to renovation works done under the supervision of Central Cultural Fund. However, geometries proposed by other researchers [10] mentioned in Table 1 are used for numerical modelling since such an assumption still gives a fair understanding of the performance of Abayagiri and Jetawana stupas. For dynamic analysis of three stupas, two dimentional numerical modelling was used since the results of dynamic analysis are to be compared with those of static analysis.

2D numerical modelling was performed using SAP2000 v.14 general purpose software package [4]. A half of the cross-section was taken with nodes located at one meter intervals both in horizontal and vertical directions. Square elements were created connecting the closest nodes with a curved area in the dome's outer surface achieved by triangular elements. Joints in the lowest nodes were defined as fixed support for static analysis. Few models were drawn for each stupa and the most suitable numerical model that matches the present shapes of the stupas was selected.

4. Observations and Results

4.1 Results of Ancient Brick Testing

Two brick samples were taken from Digavapi stupa to determine the compressive strength, specific gravity, elastic modulus and Poisson's ratio. Table 4 indicates the results obtained of brick samples of Digavapi stupa. Numerical analysis was performed using material properties of Digavapi bricks and Jetavana stupa. Table 5 shows the material parameter inputs for numerical modelling using SAP2000 software.

Table 4 – Properties of ancient bricks obtained from Digavapi Stupa

Source	Specific Gravity	Young's Modulus (GPa)	Poisson's Ratio	Compressive Strength (MPa)
Digavapi stupa	1.899	5.0	0.25	6.0

Table 5 - Material Properties used in Numerical Modelling

Material Name	Material Type	Unit Weight (kN/m^3)	Modulus of Elasticity (kN/m^2)	Poisson's Ratio
Brick-Jetavana	Other	16.9	4500	0.25
Brick-Digavapi	Other	18.6	5000	0.25

4.2 Results and Discussion of Static Analyses

SAP2000 gives four types of stress contours for the "Asolid" elements as S11, S22, S33 and S12. S11 is the radial stress, S22 is the vertical stress, S33 is the hoop stress and S12 is the shear stress. Figure 1 shows S22 vertical stress distribution of the Jetavana stupa.

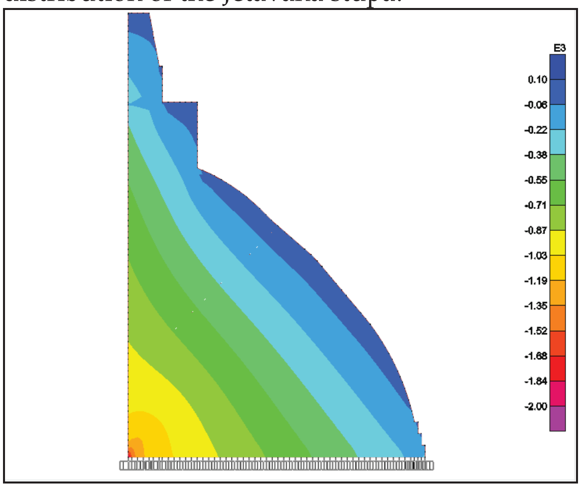


Figure 1(a) - Vertical Stresses (in MPa) of Jetavana Stupa using the Properties of Bricks of Jetawana Stupa

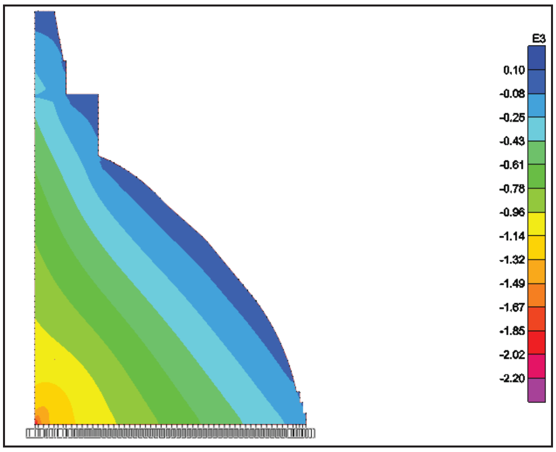


Figure 1(b) - Vertical Stresses (in MPa) of Jetavana Stupa using the Properties of Bricks of Digavapi

Figure 2 shows the locations where stresses are compared for three stupas. These locations are used in Tables 6, 7 and 8 for result comparisons.

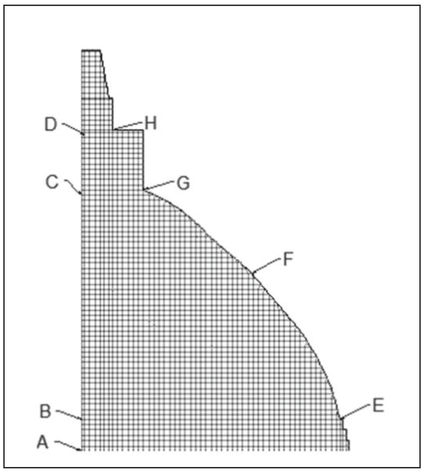


Figure 2 – Locations for Checking Vertical Stresses in the three Stupas

Figures 3 and 4 show vertical stress distributions for Abayagiri and Jetavana stupas.

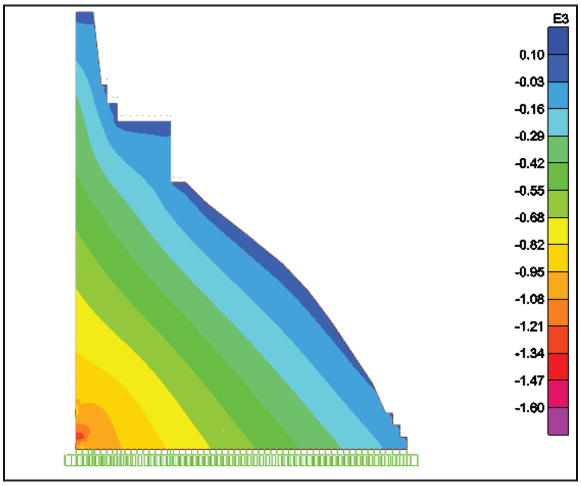


Figure 3(a) - Vertical stresses (in MPa) of Abayagiri Stupa using the Properties of Bricks of Jetavana Stupa

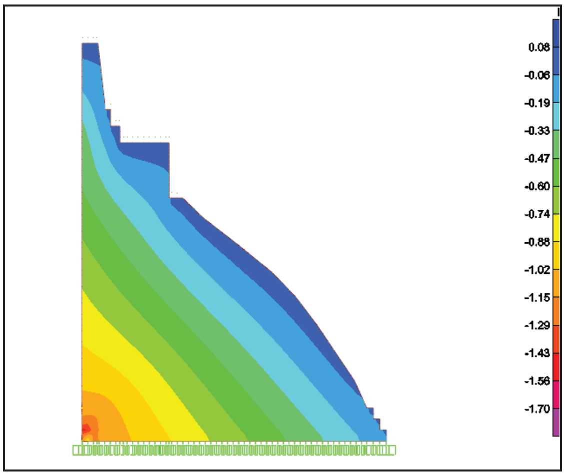


Figure 3(b) - Vertical Stresses (in MPa) of Abayagiri Stupa using the Properties of Bricks of Digavapi Stupa

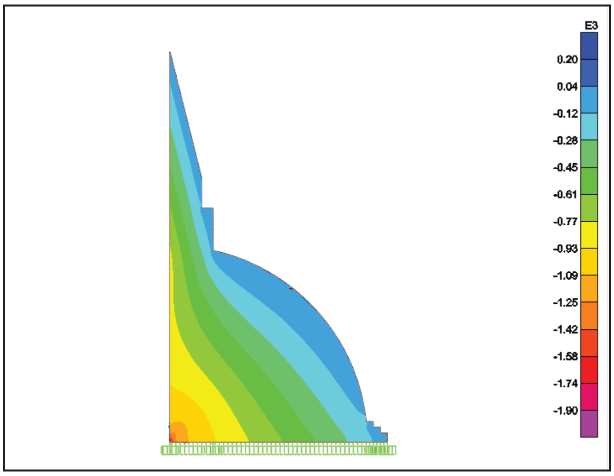


Figure 4(a) – Vertical Stresses (in MPa) of Ruwanweli Stupa using the Properties of Bricks of Jetavana Stupa

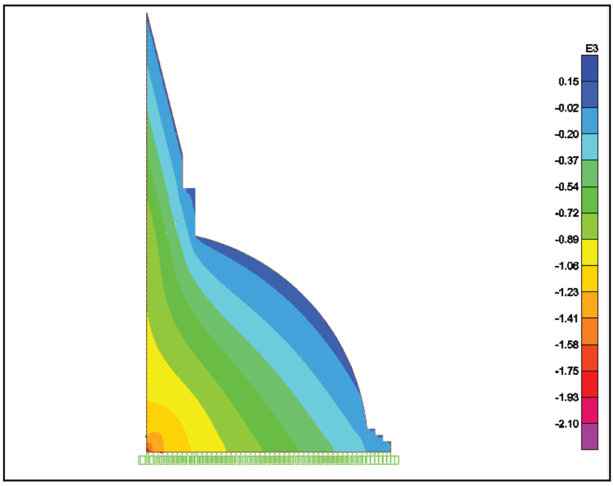


Figure 4(b) - Vertical Stresses (in MPa) of Ruwanweli Stupa using the Properties of Bricks of Digavapi Stupa

Table 6 - Obtained Vertical Stresses (S22) Distribution of Jetavana Stupa

Location	Vertical Stress (kN/m²)		Based on Properties of ancient brick from Jetavana stupa		Vertical Stress (kN/m²)		Based on Properties of ancient brick from Digavapi stupa	
	Type	Value	Capacity (kN/m²)	Applied value / Capacity	Type	Value	Capacity (kN/m²)	Applied value / Capacity
A	Compressive	1,956	8,500	23.01%	Compressive	2,156	6,000	35.93%
B	Compressive	1,086	8,500	12.78%	Compressive	1,211	6,000	20.18%
C	Compressive	521	8,500	6.13%	Compressive	592	6,000	9.87%
D	Compressive	298	8,500	3.51%	Compressive	329	6,000	5.48%
E	Compressive	119	8,500	1.40%	Compressive	131	6,000	2.18%
F	Tensile	47	850	5.53%	Tensile	52	850	6.12%
G	Compressive	152	8,500	1.79%	Compressive	170	6,000	2.83%
H	Compressive	149	8,500	1.75%	Compressive	164	6,000	2.73%

Table 7 - Obtained Vertical Stresses (S22) Distribution of Abayagiri Stupa

Location	Vertical Stress (kN/m²)		Based on Properties of ancient bricks from Jetavana stupa		Vertical Stress (kN/m²)		Based on Properties of ancient bricks from Digavapi stupa	
	Type	Value	Capacity (kN/m²)	Applied value / Capacity	Type	Value	Capacity (kN/m²)	Applied value / Capacity
A	Compressive	1,740	8,500	20.47%	Compressive	1,918	6,000	31.97%
B	Compressive	1,029	8,500	12.11%	Compressive	1,135	6,000	18.92%
C	Compressive	452	8,500	5.32%	Compressive	485	6,000	8.08%
D	Compressive	374	8,500	4.40%	Compressive	404	6,000	6.73%
E	Compressive	88	8,500	1.04%	Compressive	99	6,000	1.65%
F	Tensile	33	850	3.88%	Tensile	39	850	4.59%
G	Compressive	106	8,500	1.25%	Compressive	115	6,000	1.92%
H	Tensile	17	850	2.00%	Compressive	19	6,000	0.32%

Table 8 - Obtained Vertical Stresses (S22) Distribution of Ruwanweli Stupa

Location	Vertical Stress (kN/m²)		Based on Properties of ancient brick from Jetavana stupa		Vertical Stress (kN/m²)		Based on Properties of ancient brick from Digavapi stupa	
	Type	Value	Capacity (kN/m²)	Applied value / Capacity	Type	Value	Capacity (kN/m²)	Applied value / Capacity
A	Compressive	1,872	8,500	22.02%	Compressive	2,064	6,000	34.40%
B	Compressive	1,096	8,500	12.89%	Compressive	1,250	6,000	20.83%
C	Compressive	798	8,500	9.39%	Compressive	880	6,000	14.67%
D	Compressive	633	8,500	7.45%	Compressive	697	6,000	11.62%
E	Compressive	171	8,500	2.01%	Compressive	189	6,000	3.15%
F	Tensile	55	8,50	6.47%	Tensile	61	850	7.18%
G	Compressive	141	8,500	1.66%	Compressive	158	6,000	2.63%
H	Compressive	188	8,500	2.21%	Compressive	208	6,000	3.47%

4.3 Results and Discussion of Dynamic Analyses

For the dynamic analysis, the vertical spring constant for the supporting joints was determined as follows;

$$\text{Spring constant} = \frac{\text{Modulus of Elasticity x Area of the element}}{\text{Depth to the bed rock}}$$

Rock type beneath Jetavana stupa is Quartzite with a modulus of elasticity 31.9 GPa. Rock type beneath both Abayagiri and Ruwanweli stupa is undifferentiated charnockitic biotite gneiss with a modulus of elasticity 66.3 GPa. The average depth to the bed rock is 6 m. The width of the element in the model is 1 m.

Therefore, for Jetavana stupa,

$$\text{Spring constant} = \frac{31.9 \, x \, \pi \, / \, 4 \, x \, 1 \, x \, 10^{6}}{6}$$

$$= 4.175 \times 10^{6} \text{ kN/m}$$

and for Abayagiri, Ruwanweli stupa,

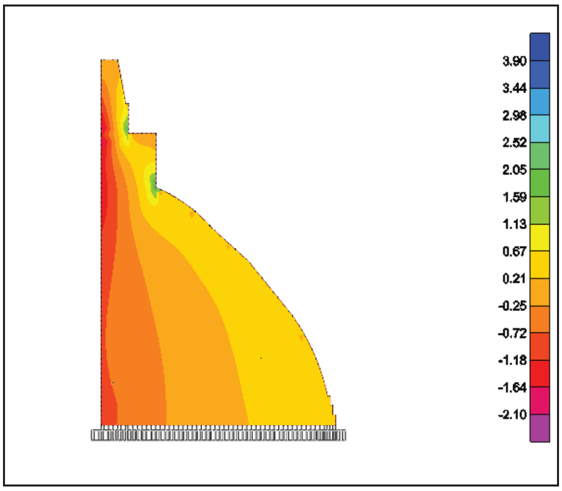
$$\text{Spring constant} = \frac{66.3 \, x \, \pi \, / \, 4 \, x \, 1 \, x \, 10^{6}}{6}$$

$$= 8.679 \times 10^{6} \text{ kN/m}$$

It is mentioned that only vertical springs were used in the dynamic analysis as acceleration data is also in up-down directions. In horizontal directions, pin supports were used. The dynamic analysis was performed as a separate analysis from the static analysis that was introduced in previous sections.

4.3.1 Dynamic Analyses with Recorded Highest Magnitude Earthquake in Sri Lanka

Vertical direction acceleration data of the earthquakes mentioned in Table 3 were input to the numerical models of three stupas and referring to the time acceleration file, maximum acceleration time is encountered. The maximum acceleration time is 35,680 s and the maximum acceleration is 5.48 x 10^{-5} g. Vertical stress distributions at the maximum time acceleration are shown in Figure 5 for three stupas. Table 9 shows the comparison of maximum stresses for three stupas.



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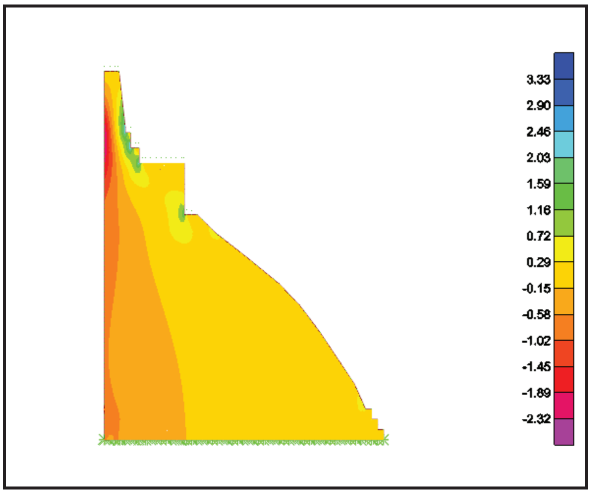

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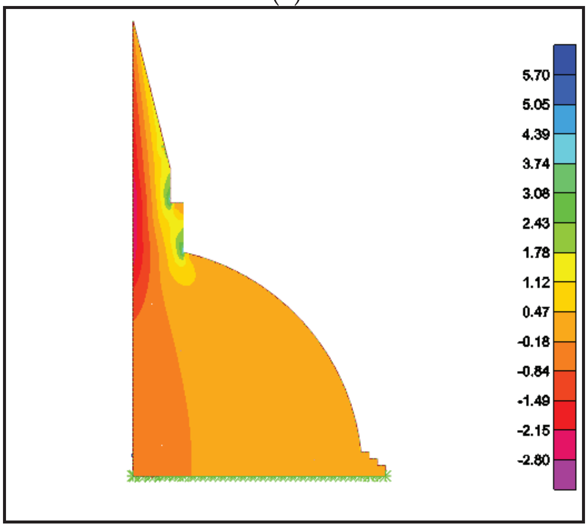


(c)

Figure 5 – Vertical stress S22 (in MPa) in Stupas due to maximum earthquake in Sri Lanka: (a) Abayagiri Stupa, (b) Jetavana Stupa, (c) Ruwanweli Stupa

Table 9 - Results of Dynamic Analysis due to Highest Magnitude Earthquake in Sri Lanka

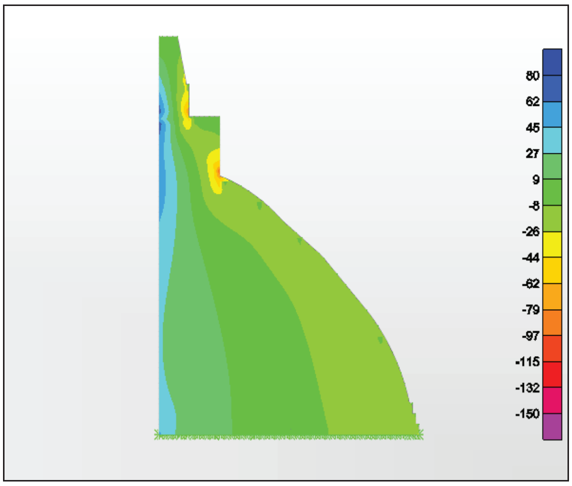
Stupa Name	Vertical stress S22		Radial stress S11		Shear stress S12	
	Max. Compressive stress (kN/m²)	Max. Tensile stress (kN/m²)	Max. Compressive stress (kN/m²)	Max. Tensile stress (kN/m²)	Negative Shear stress (kN/m²)	Positive Shear stress (kN/m²)
Abayagiri	2.30	3.20	0.60	2.70	1.02	0.66
Jetavana	2.08	3.56	0.36	2.63	0.54	1.23
Ruwanweli	2.80	5.70	0.49	4.39	1.35	2.37

4.3.2 Dynamic Analysis with Manjil Earthquake Acceleration Data

As mentioned previously, considering high unpredictability of all aspects of an earthquake, study of the worst case type scenarios was attempted in this study. Obtaining such knowledge would assist in developing means to strengthen these stupas and would broaden the understanding of such structures under seismic loads, for the future design of new stupas.

Dynamic analysis was extended to analyse with magnitude 7.4 of Manjil earthquake to observe the stress distribution in the three stupas. A vertical direction acceleration file was selected and data were input as indicated in Table 3.

Maximum acceleration time was extracted from the acceleration file. The maximum acceleration occurred at the time of 7.94 s and the maximum acceleration value was 0.4 g. Figure 6 depicts the stress contours of vertical stress (S11) of three stupas for the maximum acceleration of 0.4 g. Comparison of vertical stress of three stupas is given in Tables 10 and 11.



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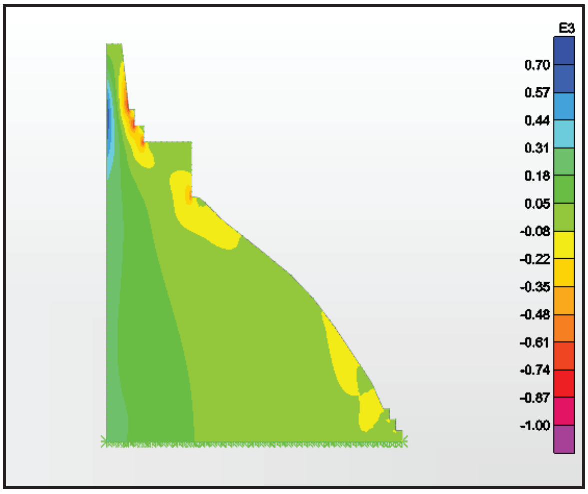

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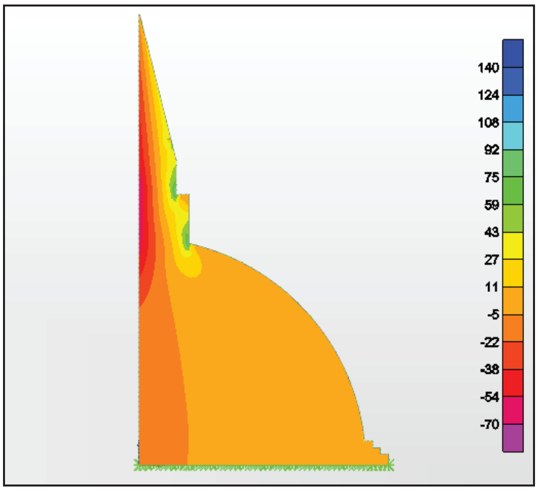

(c)

Figure 6 – Under Simulated Manjil Earthquake Vertical stress S22 (in MPa) of (a) Abayagiri Stupa, (b) Jetavana Stupa, (c) Ruwanweli Stupa

Table 10 - Obtained Maximum Vertical Stresses with Respect to Manjil Earthquake (0.4 g)

Name of stupa	Maximum vertical stress		Capacity of the Brick or Concrete (kN/m²)	Applied value / Capacity
	Type	Value (kN/m²)		
Abayagiri	Compression	982.56	6,000	16.38%
	Tension	692.82	850	81.51%
Jetavana	Compression	142.45	6,000	2.37%
	Tension	76.76	850	9.03%
Ruwanweli	Compression	66.08	6,000	1.10%
	Tension	136.29	850	16.03%

Table 11 - Results of Dynamic Analysis with Respect to Manjil Earthquake (0.4 g)

Stupa Name	Vertical stress S22		Radial stress S11		Shear stress S12	
	Max. Compressive stress (kN/m²)	Max. Tensile stress (kN/m²)	Max. Compressive stress (kN/m²)	Max. Tensile stress (kN/m²)	Negative Shear stress (kN/m²)	Positive Shear stress (kN/m²)
Abayagiri	982.56	690.82	800.27	171.09	302.23	283.37
Jetavana	142.45	76.76	97.03	13.44	45.34	19.82
Ruwanweli	66.08	136.29	11.64	105.09	32.30	56.68

5. Overall Discussion

5.1 Two Dimensional Static Analysis

Considering the 2D static analysis of Abayagiri, Jetavana and Ruwanweli stupas, it was observed that the maximum compression is in the bottom center and the maximum tension is in the middle of the curved surface of the dome (Point F in Figure 2). The highest values for the maximum tensile stress over the capacity of the ancient bricks in Jetavana, Abayagiri and Ruwanweli stupas are accordingly 6.12%, 4.59% and 7.18%, respectively. Therefore, it is evident that the paddy heap shape is more stable than the bubble shape. It verifies the results of previous researchers on static analysis of stupas.

In Abayagiri and Jetavana stupas, renovation work was done to present height instead of restoration to their original height due to objections from archaeologists. The ratios of maximum compression over capacity of ancient bricks in Jetavana, Abayagiri and Ruwanweli stupa are accordingly 35.93%, 31.97% and 34.40% (Point A in Tables 6, 7 & 8). Therefore, it could be concluded that the height of those stupas could be further increased since maximum compression over the capacity of the ancient brick has not reached unity.

Further, the inverse of the applied value of tension or compression over the capacity of brick can be introduced as a factor of safety of a stupa. Accordingly, factors of safety in Jetavana, Abayagiri and Ruwanweli stupas are 2.78, 3.12 and 2.91, respectively, for static analysis. Since, in reference to BS 5628 part 1(1992) on masonry, the partial safety factor for the material strength is 3.5, the factors of safety in Jetavana, Abayagiri and Ruwanweli stupas closely match the BS5628 part 1 (1992) requirements too.

5.2 Two Dimensional Dynamic Analysis with magnitude 4.7 Earthquake

The highest Magnitude of 4.7 earthquake that occurred on the 19th November 2011 was around 500 km from Sri Lanka. The time acceleration data were collected from Mahakanadarawa seismic station which was located on Mahakanadarawa antiform. Rock type in the Mahakanadarawa area is not similar to the Mahamewna Uyana area where three stupas are located. There is a shear zone across the Tissa-wewa tank and Abhaya-wewa tank which is close to Ruwanweli stupa. Therefore, the magnitude of the possible highest earthquake can be greater than 4.7.

It was observed that the maximum compressive and tensile stresses in the vertical direction are negligible compared with the capacity of the ancient bricks. Therefore, it can be concluded that three stupas are in a safe condition for the maximum possible earthquake based on previous records. As such, there is no need to consider any static and earthquake load combination for the study.

In Abayagiri, Jetavana and Ruwanweli stupas, maximum compression and tension occurred above the dome. Maximum compression and maximum tension in the vertical direction in Ruwanweli stupa are higher than that of Abayagiri and Jetavana stupas. This verifies the conclusion stated in static analysis that the paddy heap shape is more stable than the bubble shape.

5.3 Two-Dimensional Dynamic Analysis under Magnitude 7.4 Earthquake

It was observed that the maximum vertical tensile stress that occurred in the Abayagiri stupa is 81.5% of the tensile capacity of the ancient bricks used in construction. Hence, Abayagiri stupa may not be stable under magnitude 7.4 earthquake acceleration owing to its lower factor of safety.

Other stresses, namely, radial stress (S11) and shear stress (S12) due to the magnitude 7.4 Manjil earthquake are less than vertical stresses (S22). Therefore, it can be concluded that further studies on Abayagiri stupa under possible seismic effects are necessary.

6. Conclusions and Recommendation

Considering the stress distribution with static and dynamic analyses, it can be concluded that the paddy heap shape of stupas is more stable than bubble shape of stupas. Further, outer core masonry structure is not suitable for large stupas.

Considering the past records of earthquakes in Sri Lanka, it can be stated that all three stupas are in safe condition under magnitude 4.7 earthquakes. However, the maximum possible earthquake in the Mahamewna Uyana area where three stupas are located, can be greater than magnitude 4.7 due to the existing shear zone located very close to Mirisawetiya stupa. Referring to the stress distribution with the magnitude 7.4 Manjil earthquake, both Jetavana and Ruwanweli stupas are in a safe condition. The maximum possible earthquake magnitude that each stupa can withstand cannot be predicted at this instant and further studies should be carried out with many earthquake signatures as well.

In the Anuradhapura Mahamewna Uyana area, the depth from the ground surface to the bedrock is within a few meters. Numerical models were drawn to the structure above the ground surface as the material properties and geometrical data of foundations were not possible to be obtained accurately. It is recommended to carry out the studies, including the foundations of the stupas, considering soil-structure interaction.

This study was restricted to three stupas with bubble and paddy heap shapes. It is recommended to carry out further studies involving three-dimensional modelling to assess the performance under earthquake loading of stupas. Further, it is also recommended to perform possible load combinations of static and dynamic loading which suit Sri Lankan conditions to get more accurate results.

Selection of acceleration data is based purely on recorded maximum histories in Sri Lanka. Such approach will give a clear insight to the practical earthquake resilience of the stupas. Further, it is possible to predict acceleration histories based on return period concepts (14). However, it was not considered in this study. Authors recommend performing such studies in future.

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