SURGE PROTECTION OF GIANT STUPA STRUCTURES

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November 2019

ABSTRACT

This project involves analyzing lightning risks related to giant stupa structures, which involved analyzing the effects of lightning to the stupa structure itself and the people and other structures in the surrounding area. The existing lightning protection system was considered when performing this risk analysis.

The main outcomes of the project could be listed as,

- Review of standards related to lightning protection.

- Design of Computer-Aided Design (CAD) models for the following stupas and the citadel in Anuradhapura in present dimensions and ancient the dimensions of stupa structures which were built around 377BC -1017AD
    1. Ruwanweliseya
    2. Abayagiriya
    3. Jethawanaramaya
    4. Mirisavetiya
    5. Royal Citadel of King Vijayabahu the 1st

- Analysis of the existing lightning protection system using
    - Protective angle method
    - Rolling sphere method
    - Modified rolling sphere method
    - Electrical field distribution-based analysis

  Considering the following factors
    - Protection of stupa structure
    - The people around the stupa structure

- Propose any improvements (If necessary) to minimize the damage due to a lightning strike.

ACKNOWLEDGEMENTS

We want to express our sincere gratitude to our project supervisor Prof M.A.R.M Fernando for the guidance he gave us on the theoretical background, research materials, and other information related to this project.

Then we would like to thank Dr. Waranatha L. Abeygunasekara for guiding us with the help related to the COMSOL Multiphysics engine-related modelling. We would also like to thank prof Sirinivasan Venkatesh from VIT University India for providing us with the Auto Cad files and the research materials on their research about heritage sites lightning protection.

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LIST OF ABBREVIATIONS

3D	Three Dimensional
AC	Alternative Current
CAD	Computer-Aided Design
CC	Cloud to Cloud
CG	Cloud to Ground
IEC	International Electro technical Commission
LEMP	Lightning Electromagnetic Impulse
LPC	Lightning Protection Components
LPL	Lightning Protection Level
LPS	Lightning Protection System
LPZ	Lightning Protection Zones
MRSM	Modified Rolling Sphere Method
RSM	Rolling Sphere Method
SPD	Surge Protective Device
SPM	Surge Protective Measures

CHAPTER 1
INTRODUCTION

This project aims to design 3D models of Giant stupa structures and analyses the behavior of lightning effects around the structure. This involves analyzing risk factors due to lightning to the people around the structures. The analysis was performed with,

- Stupa structures using present dimensions
- Stupa structures using ancient dimensions
- Citadel of King Vijayabahu I
- Ancient stupa structures with the Citadel of King Vijayabahu I

The risk analysis was performed, and recommendations were provided upon these developed models.

1.1 WHAT IS A LIGHTNING SURGE?

Lightning is a natural electrical discharge phenomenon. In Sri Lanka, lightning can only be observed in thunderstorms. However, in some parts of the world, lightning can also be observed in sandstorms and volcanic eruptions. During thunderstorms, electrically charged molecules in water droplets and ice are separated due to strong winds. These electrical charges are accumulated in the atmosphere and neutralized through electrical discharge. This process is known as lightning[1].

Figure 1. 1 Lightning during a thunderstorm*

1.2 TYPES OF LIGHTNING SURGES

Lightning surges can be categorized according to the location of positive and negative charges when the lightning occurs.

*image credit- https://wallpaperscraft.com/download/lightning_thunderstorm_city_lights_126486/3840x2400

1.2.1 Cloud to the ground (CG) lightning

This is the most common type of lightning. Hence, most of the studies on lightning are done for CG lightning. When opposite charges accumulate on the cloud and the ground, CG lightning occurs[2], [3]. Different types of CG lightning are shown in Fig 1.2. (a), (b), (c) and (d)

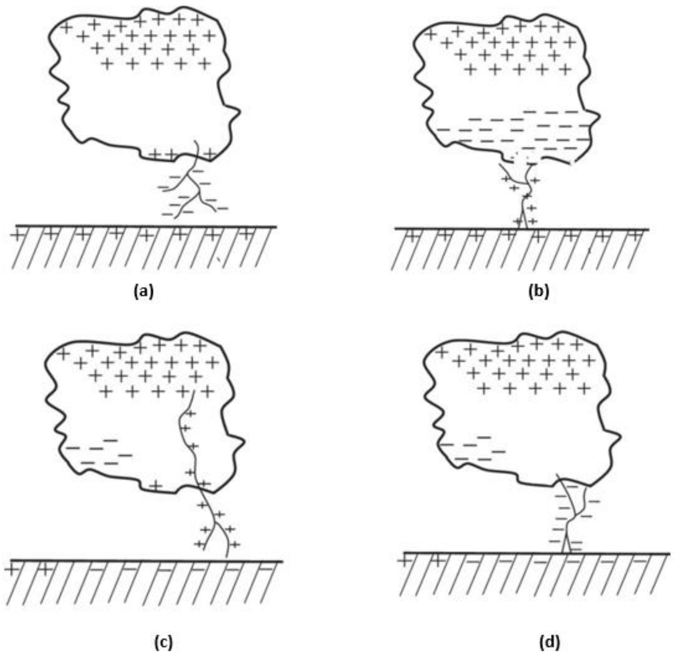


Figure 1. 2 Different types of CG lightning

(a)	**Downward negative lightning**	**(b)**	**Upward negative lightning**
(b)	**Downward positive lightning**	**(d)**	**Upward positive lightning**

1.2.2 Cloud to cloud (CC) lightning

Figure 1. 3 Cloud – cloud lightning

Lightning occurs between two or more separate clouds. When lightning occurs in different regions of the same cloud, it is called as Intra-cloud lightning.

1.2.3 Cloud to air lightning

This type of lightning occurs when the surrounding air of a charged cloud is oppositely charged, and the electric field is strong enough for the cloud to air lightning to occur.

Figure 1. 4 Cloud - air lightning

1.2.4 Cloud – space lightning

An electric discharge occurs between the upper parts of a cloud, and the ionosphere belongs to this category. This is a rare phenomenon, and this type of lightning is also known as jet lightning or ionospheric lightning.

Figure 1. 5 Cloud – space lightning

1.3 EFFECTS OF LIGHTNING SURGE

Lightning can affect, and cause damages to,

- Buildings
- Electrical and electronic equipment
- Living beings

If a building does not have a lightning rod for protection, lightning will typically strike at the peak point of the building and look for a way to earth in an uncontrolled way through antennas, concrete structures, pipes, and cables. This current flow may cause sparks, breakages and damage to people and equipment inside the building. In such cases, if the structure contains toxic, flammable, or explosive products or being able to extend the damage beyond the impacted structure, then the hazard increases[4].

Figure 1. 6 A building heavily damaged by lightning

When the lightning current dispersed into the ground, it can cause severe injuries to people and might even cause death due to the step voltage, which is further discussed in chapter 2. Electrical and telecommunications supply lines (telephone, television, Internet), as they penetrate the structures from the outside, can introduce part of the lightning current into a building, even if the building has lightning rods. Hence including surge protection devices within the lightning protection system is essential if lines are aerial and are not shielded. Lightning current and over voltages in lines may affect safety equipment (elevator safety brakes in high-rise buildings, for instance) or cause sparks in areas with explosion risks. So, to avoid the consequences of lightning strikes on structures and supply lines, a system of protection against lightning is necessary, consisting of lightning rods, conductors and accessories, surge protectors, and an adequate earthing system.

1.4 STUPA STRUCTURES

1.4.1 What is a stupa structure?

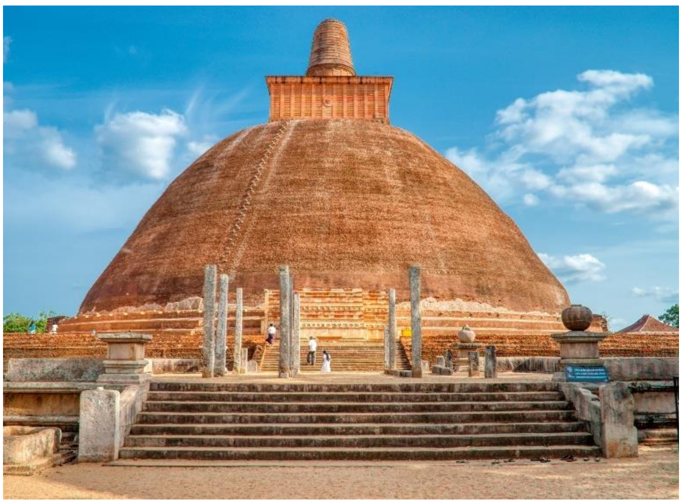


Figure 1. 7 Jethawanaramaya stupa in Anuradhapura

The stupa is one of the most recognizable forms of Buddhist architecture, marking the landscape in all Buddhist countries. These are hemispherical structures housing sacred relics associated with the Lord Buddha.

1.4.2 Parts of a stupa structure

In Sri Lanka, there are six main types of stupa structures that can be identified, and they are named according to their shape of the dome or body of the stupa.

Several main components can be seen in stupa structures in Sri Lanka.

01. Basal rings (Pesa Walalu)
    Cylindrical terraces are built at the bottom of the stupa structure, and typically there are three.

02. Dome (Garbhaya)
    Dome is built on the top of the basal rings, and according to the stupa structure, the shape of the dome is changed. A relic chamber is built inside this dome.

03. Square Chamber (Hatharas Kotuwa)
    This part is also used to enshrine the relics.

04. Cylinders (Dewatha Kotuwa)
    This part is built on the top of the square chamber, and figures of deities are carved on its surface.

05. Spire (Koth Karella)
    In ancient times, the stupa was smaller in size, and people used to construct umbrellas to protect them from rain and direct sunlight. When stupa becomes more substantial, these umbrellas were replaced by the spire.

06. Mineral (Kotha)
    A metal structure is typically placed in the peak of the stupa, which is often called as silumina. According to Mahavansa, this pointed metal cap believed to have adequately protected stupa from the lightning.

07. Crystals
    Precious crystal or gemstones were traditionally placed at the top of the kotha for decoration purposes.

08. Surge arrestors
    A copper rod is implemented near the visible top of the stupa for lightning protection, and it is carefully grounded through a down conductor.

Table 1. 1 Different types of stupa structures in Sri Lanka

Structure type	The shape of the Structure	Example in Sri Lanka
Bubulakara	Bubble	Ruwanveli seya Kiri vehera Rankoth vehera
Ghantakara	Bell	Thuparamaya Ambasthala dagaba at Mihinthale
Dhanyakara	Paddy heap	Kelaniya
Ghatakara	Pot	Situlpawwa Somawathiya Katharagama
Padmakara	Lotus	Wijayarama Puliyankulama Indikatu seya
Palandawakara	Onion	Nadigamvila stupa

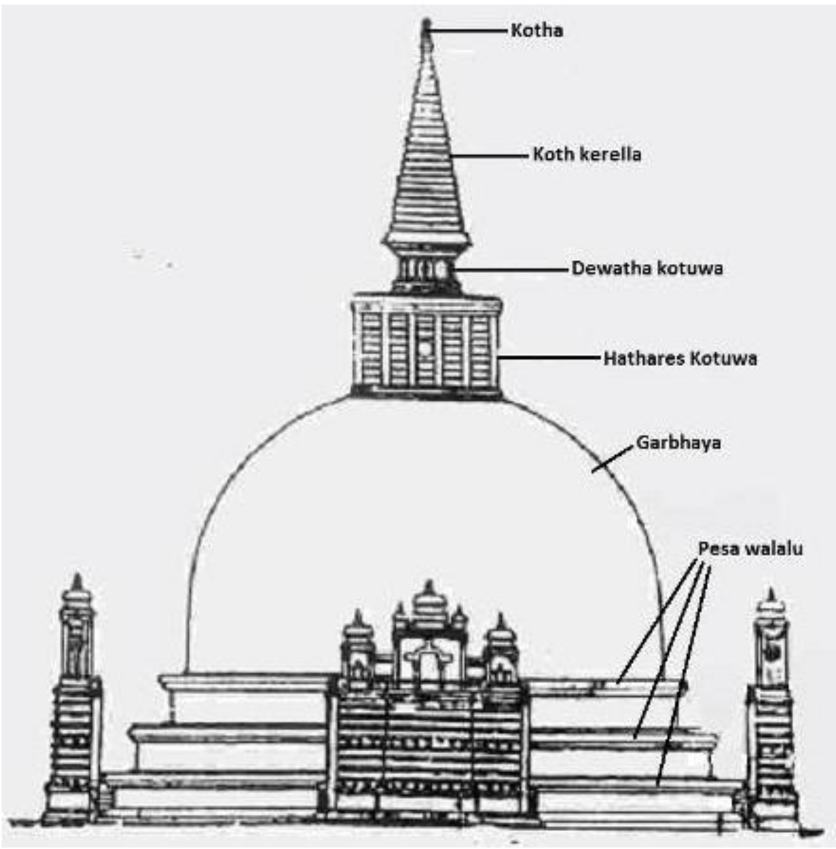


Figure 1. 8 Main components of stupa – simple diagram

1.4.3 Ancient Anuradhapura Kingdom

Figure 1. 9 Location of Anuradhapura Kingdom

Figure 1. 10 Ruwanweliseya Stupa

The Anuradhapura Kingdom is the first kingdom established in Sri Lanka by King Pandukabhaya in 377B.C[5]. Buddhism played an influential role in the Anuradhapura period, influencing its culture, laws, and methods of governance. The famous structures Ruwanweliseya, Jethavana stupas, and other large stupas, large buildings like the Lovamahapaya landmarks demonstrates the Anuradhapura period's advancement in technology and engineering skills.

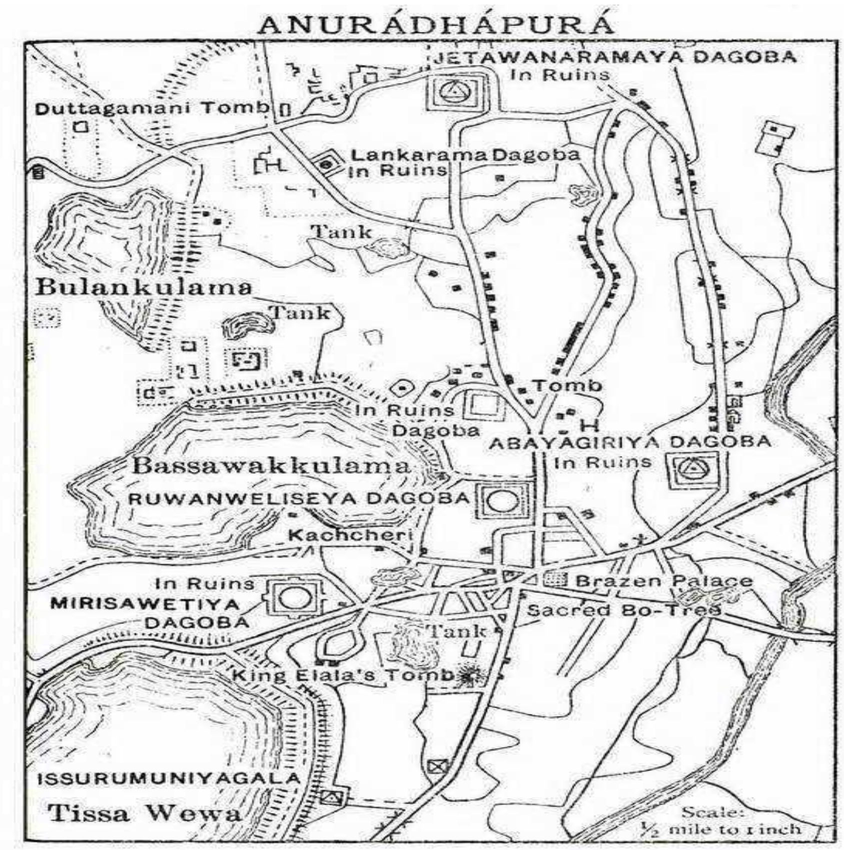


Figure 1. 11 Map of ancient Anuradhapura Kingdom

1.5 SOLIDWORKS

SOLIDWORKS is computer-aided design software that is primarily used for solid modeling and analysis of such structures. These designs can be used to generate engineering drawings, 3D printing of the solid models, or for demonstration purposes. This also allows the designers to further develop their designs without having to build it in the real world. The design interface of SOLIDWORKS software is shown in figure 1.12

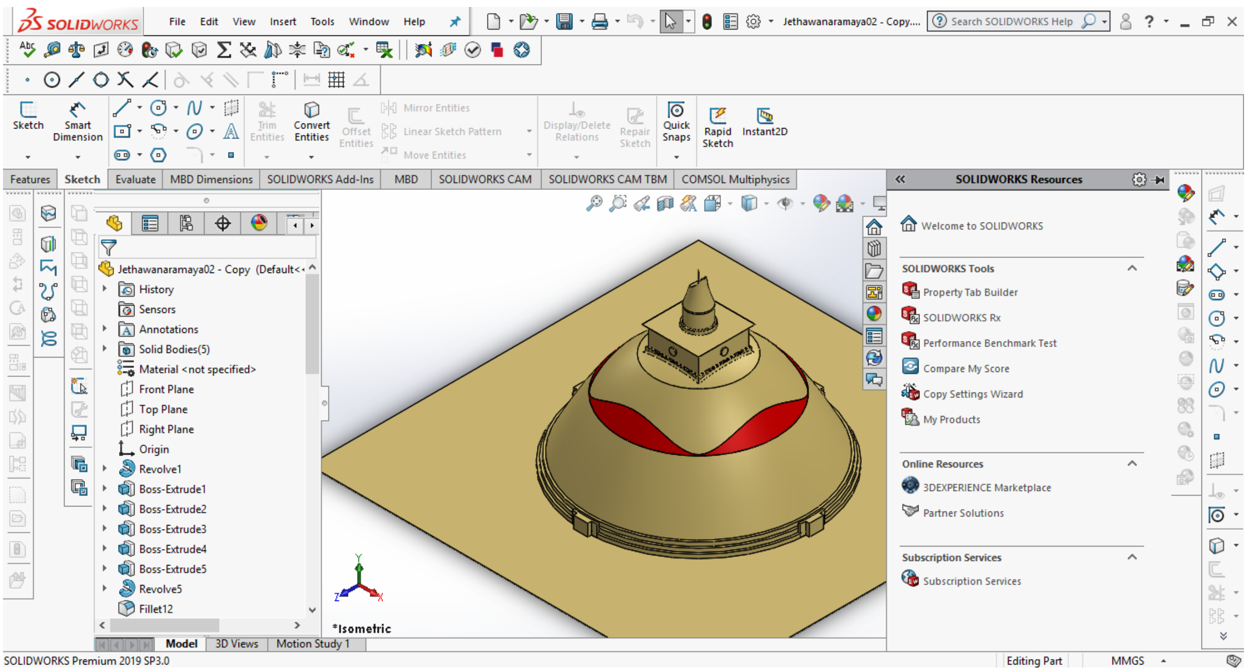


Figure 1. 12 SOLIDWORKS interface

1.6 COMSOL MULTIPHYSICS

COMSOL Multiphysics software package is a simulation environment software that is capable of performing multiple numbers of applications. This software can be used to model, simulate, and solve scientific and engineering problems such as chemical reactions, mechanics, fluid flow, acoustics, and electrical field distributions. The user interface for the COMSOL Multiphysics engine is shown in figure 1.13.

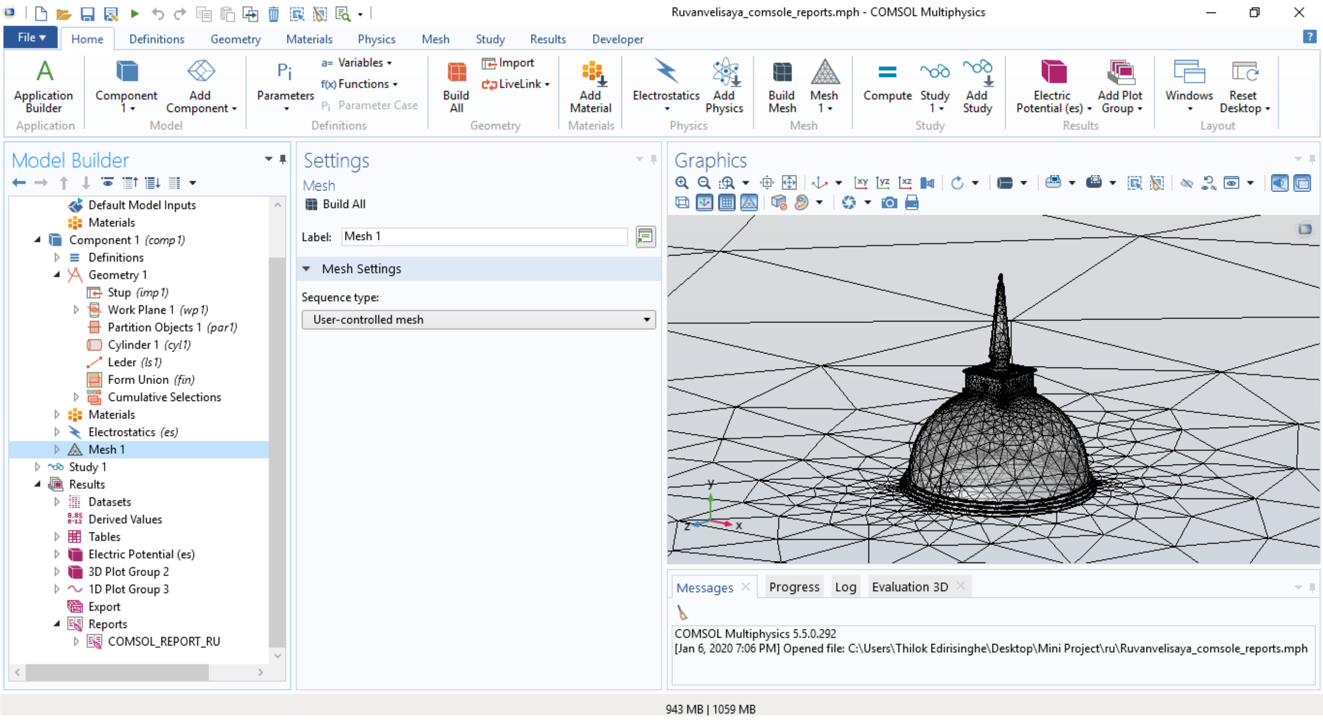


Figure 1. 13 User interface of the COMSOL Multiphysics software

1.7 WORK CARRIED OUT

To meet the objectives, the following activities were carried out according to the schedule represented by the Gantt chart in Table 1.2.

- Activity 1 – Review of fundamentals related to lightning standards
- Activity 2 – Design of stupa structures using SOLIDWORKS 3D
- Activity 3 – Integration of the 3D models into COMSOLE Multiphysics engine
- Activity 4 – Analysis of protection using the Protective Angle Method
- Activity 5 – Analysis of protection using Electric field distribution
- Activity 6- Design of ancient Stupa structures
- Activity 7- Analysis of protection of ancient stupas using geometric models
- Activity 8- Electric field-based analysis of Anuradhapura kingdom with the citadel and stupas

Table 1. 2 Gantt chart

Activity	02/12-08/12	09/12-15/12	16/12-22/12	23/12-29/12	30/12-05/01	06/01-12/01	13/01-19/01
Review of fundamentals related to lightning standards							
Design of present stupa structures using Solid works 3D							
Integration of the 3D models into COMSOLE Multiphysics engine							
Analysis of protection using the protective angle method, RSM, MRSM							
Analysis of protection using Electric field distribution							
Development and analysis of ancient stupa structures using Geometric and electric field distribution methods							
Development of electric field distribution of geographic area with the citadel included							
Preparation of final report and finalizing of analysis							

CHAPTER 2
GENERAL OVERVIEW OF LIGHTNING AND PROTECTION

2.1 METHODS OF DAMAGE DUE TO LIGHTNING

There are several ways a person could injure or die due to a lightning strike.

2.1.1 Direct Strike

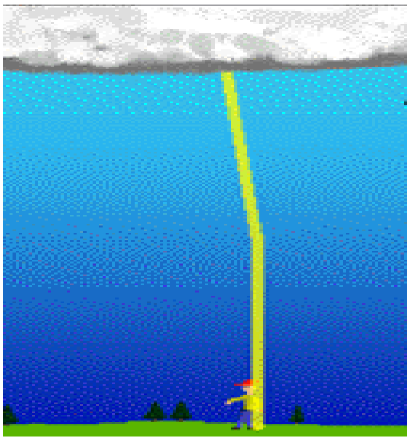


Figure 2. 1 Direct lightning strike

A person struck directly by lightning, then becomes a part of the main lightning discharge channel. Direct strikes, in most cases, occur to victims who are in open areas. Direct strikes are not as frequent as the other ways people are struck by lightning, but they are potentially the deadliest.

2.1.2 Side Flash

Figure 2. 2 Side flash

When lightning strikes into a taller object near the victim, and a portion of the current jumps from taller objects to the victim, which is called as the slide flash. The person acts as a '*short circuit*' for some of the energy in the lightning discharge. Typically, Side flashes occur when the victim is within a foot or two of the objects that has been struck by lightning.

2.1.3 Touch potential

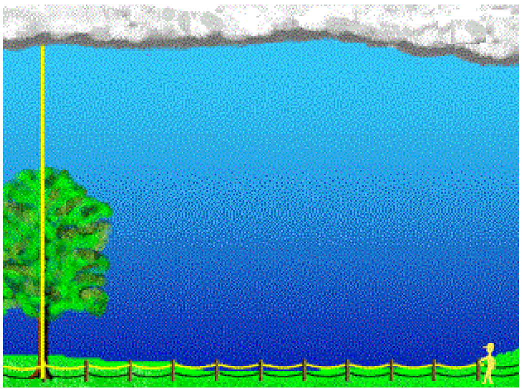


Figure 2. 3 Touch potential

Lightning can travel long distances through metal surfaces and wires. Even though the metals do not attract lightning, it can provide a path for lightning to travel. Most of the indoor lightning casualties and some outdoor casualties were caused due to conduction.

2.1.4 Side Potential / Ground current

Figure 2. 4 Side potential

If lightning strikes a tree or other object, The surge travels to the ground surface, then outward from that point and along the ground surface. This is known as the ground current. Any person, animal, or livestock on the ground outside near a lightning strike is potentially a victim of ground current.

2.1.5 Aborted upward streamers

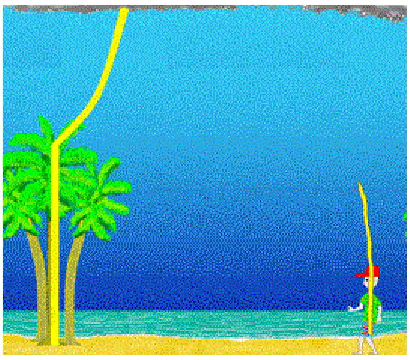


Figure 2. 5 Aborted upward streamer

Upward Streamers develop as the downward-moving leader approaches towards the ground surface. Typically, only one of these streamers makes contact with the leader and provides the path for the return stroke. When the main channel discharges, all the other streamers in the area do likewise. If a person or an animal is part of one of these up streamers, they may be killed or injured during the discharge of the streamer even though the lightning channel between the cloud and the upstreamer was not complete.[6]

2.2 METHODS TO PROTECT AGAINST LIGHTNING

The most common lightning protection system for a structure is to install a lightning rod and ground it through a down conductor system[6].

Lightning rods come in many different forms

- Hollow
- Solid
- Pointed
- Rounded
- Flat strips

All lightning rods are made of conductive materials, such as copper and aluminum. Copper and alloys containing copper are the most common materials used in lightning protection.

2.2.1 GENERAL TIPS FOR PROTECTION AGAINST LIGHTNING

- ❖ Staying indoors in a closed shelter is the best thing to do when there is lightning[7], [8].
- ❖ Staying in a fully enclosed vehicle also protect against lightning since it acts as a faraday cage.
- ❖ It is wise to suspend outdoor activities for at least 30 minutes after the last clap of thunder has occurred.
- ❖ If no shelter is available near the area, crouch low, with as little of the body touching the ground as possible.
- ❖ Never stand near tall structures, particularly metal ones which can act as a conductive path. Avoid lone trees, flagpoles, fences, antennas and telephone poles.
- ❖ In case of a deep in the forest, retreat underneath a group of small trees, preferably surrounded by taller ones.
- ❖ In more open areas, retreat and crouch down in the closest dry, low area, and squat in a baseball catcher’s position, and minimize contact with the ground and touch the heels of your feet together. If your hair begins to straighten on end or skin starts to tingle, a lightning strike is imminent. Immediately get into the safety position.
- ❖ When staying inside a building, it is recommended to stay away from concrete floors or walls without isolation. Lightning may travel through any metal wires or bars in concrete walls or flooring; hence being indoors does not automatically protect from lightning.
- ❖ It is advisable to avoid water taps and sinks during a thunderstorm. Lightning can travel through plumbing.
- ❖ Avoid electronic equipment of all types. Lightning can travel through electrical systems and radio and television reception systems, such as antennas.

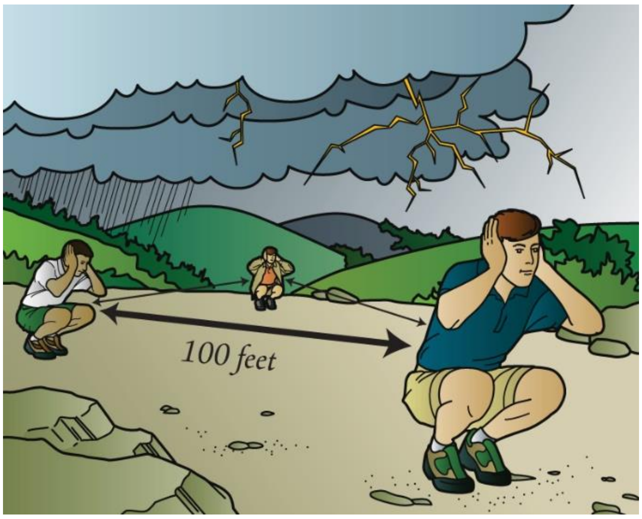


Figure 2. 6 Lightning safety position

2.3 IMPORTANCE OF ANALYZING LIGHTNING EFFECTS

Lightning is a disastrous natural phenomenon which results in loss of lives, damages to structures and causes financial losses, damaged electrical systems. To minimize these damages and prevent losses, it is essential to study lightning and analyses lightning effects. These studies enable us to determine areas that are not protected by current lightning protection systems and provide solutions/recommendations on how to improve the protection based upon the analysis.

2.4 LIGHTNING PROTECTION STANDARDS

IEC/BS EN 62305 is the worldwide recognized standard for lightning protection system (LPS) design, installation, and maintenance. BS EN 62305 is the British edition of the European standard and is derived from the IEC document[9]. There are also some other standards such as,

- BS 6651 was the British standard before the introduction of BS EN 62305. Which was First issued in 1985, then revised in 1992, 1999, and further amended in 2005; before being withdrawn on 31st August 2008.
- NFPA 780, which is a Standard for the Installation of Lightning Protection Systems, formerly known as NFPA 78, The Lightning Protection Code, is an industry-wide standard that has been revised numerous times since the first revision in 1904. Recent articles about the theories of lightning have cast serious doubts about the validity of the underlying technology and science underlying traditional lightning protection systems.
- BS 7671 provides Requirements for Electrical Installations
- BS 7430 is a Code of practice for protective earthing of electrical installations
- IEC/BS EN 61643 series provides conformity requirements for surge protection devices

2.5 LIGHTNING PROTECTION SYSTEMS

The primary function of a lightning protection system is to provide fire protection and structural damage protection by preventing a hot, explosive lightning channel from passing through building and to prevent persons in buildings from getting injured or even killed[10]. An overall lightning protection system consists of external lightning protection (lightning protection/earthing) and internal lightning protection (surge protection).

2.5.1 External lightning protection

The function of external lightning protection is to,

- Interception of direct lightning strikes using the air termination system
- Safely discharging of lightning current to earth via a down-conductor system
- Distribution of the lightning current in the ground via an earth-termination system

1) Air termination system

This is a conducting device mounted at or above the highest point of a building or a structure, to protect the structure by discharging of atmospheric electric charges.

Figure 2. 7 Multi-point copper lightning arrester

2) Down conductor system

Consist of copper or aluminum conductors. It should take the directs route to the earth termination system from the air termination system. The greater the number of down conductors, the better they share the lightning current.

Figure 2. 8 Down-conductors

3) Earth termination system

It is a continuation of air termination and down conductor systems. The function of earth termination systems is the dispersion of lightning current safely and effectively into the ground.

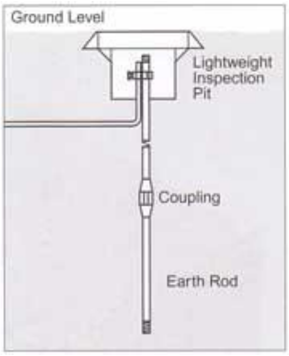


Figure 2. 9 Earth rod

4) Surge Counters

Lightning protection systems in the stupas use surge counters. By using this, it can determine how many times the structure had protected against lightning by the LPS, and when the maintenance of the system should be carried out.

Figure 2. 10 Surge counter

2.5.2 The internal lightning protection system

The internal lightning protection system prevents dangerous sparking in the structure by establishing equipotential bonding or separating the LPS components from other electrically conductive elements. Equipotential bonding reduces the potential differences in lightning currents. This is accomplished by connecting all the isolated conducting parts of the installation through conductors or surge protection devices.

Surge protection devices

The Surge Protection System (SPD) is a part of the safety system for electrical installations. SPDs are used for electric power supply networks, telephone networks, and automatic control and communication buses. This device is connected to the power supply circuit of the loads it has to protect in parallel and is commonly used and the most efficient type of overvoltage protection.

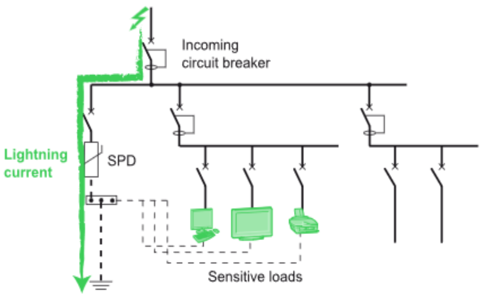


Figure 2. 11 SPD connected in parallel

CHAPTER 3
LITERATURE REVIEW

3.1 LIGHTNING SURGE

Lightning is an electrostatic discharge that occurs naturally, during which two electrically charged regions in the atmosphere or ground temporarily equalize themselves, resulting in instant release of energy. Lightning starts with a step leader, and it can be either cloud initiated or tall structure initiated.

When electric charges are built up in thunderclouds to such level that could break atmospheric insulation, an electric discharge eventually occurs between these clouds or between the clouds and the ground. An electric current of a surge can reach 5kA to 200kA, and typically it is 30kA. Lightning surge can be explained as a function of current.

3.1.1 Upward leader initiation

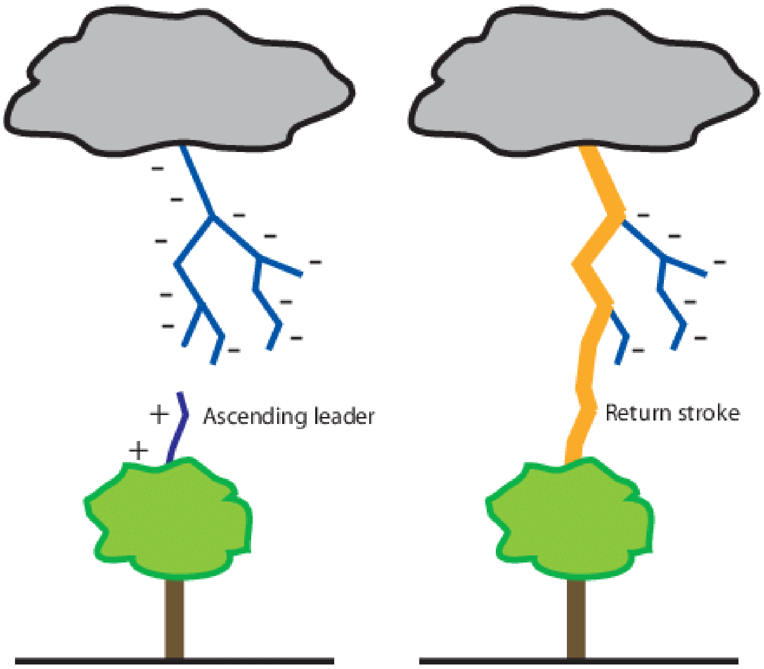


Figure 3. 1 Upward leader initiation and return stroke

As the stepped leader approaches towards the ground, carrying some coulombs of the negative charge, a significant positive charge is induced below it, creating an upward-moving discharge that spans about 30-50 meters long; when it comes up to meet it. The upward-moving discharge position determines what ground point the lightning is hitting, so lightning rods are used to initiate this discharge to provide some control over the strike location. When the stepped leader is in contact with the upward leader, an aggressive, high-current discharge flows to the ground. The extremely luminous discharge then travels back in the return stroke up the leader[11].

3.2 STRUCTURE OF BS EN/IEC 62305

The IEC standard 62305 consists of 4 main categories.

1. General principles
2. Risk management
3. Physical damage to structures and life hazard
4. Electrical and Electronic systems within the structure

3.3 GENERAL PRINCIPLES

It is an introduction to the other parts of the standard and mainly describes how to design a Lightning Protection System (LPS) following the accompanying parts of the standard.

3.3.1 Sources, Damage and, loss

Sources

- S1 Flashes to the structure
- S2 Flashes near to the structure
- S3 Flashes to a service
- S4 Flashes near to a service

Damage

- D1-Injury of living beings due to step and touch voltages
- D2-Physical damage (fire, explosion, mechanical destruction, chemical release) due to lightning current effects including sparking
- D3-Failure of internal systems due to Lightning Electromagnetic Impulse (LEMP)

Losses

- L1-Loss of human life
- L2-Loss of service to the public
- L3-Loss of cultural heritage
- L4-Loss of economic value

Table 3. 1 Damage and loss in a structure according to different points of a lightning strike

Point of strike	Source of damage	Type of damage	Type of loss
Structure	S1	D1 D2 D3	L1, L4** L1, L2, L3, L4 L1*, L2, L4
Near a structure	S2	D3	L1*, L2, L4
Service-connected to the structure	S3	D1 D2 D3	L1, L4** L1, L2, L3, L4 L1*, L2, L4
Near a service	S4	D3	L1*, L2, L4

* For structures with the risk of explosion and for hospitals or other structures where failures of internal systems immediately endanger human life.

** Only for properties where animal lives may be lost.

3.3.2 Design criteria

The optimal lightning protection for a structure and its connected services would be to enclose the structure in an earthed and perfectly conductive metal shield (box) and provide sufficient bonding of any connected services at the point of entry into the shield. Essentially, this would avoid the penetration of the lightning current and the electromagnetic field generated into the structure. In practice, however, it is not possible, or it is not cost-effective.

3.3.3 Lightning Protection Levels (LPL)

Four protection levels have been determined. For each of these four levels, it has set minima and maxima of lightning current parameters. The maximum values are used for product design, such as lightning protection modules and Surge Protective Devices (SPDs). For each level, these four levels of minimum value, the lightning current were used to derive the radius of the rolling sphere.

Table 3. 2 Lightning current for each LPL based on 10/350 μs waveform

LPL	I	II	III	IV
Maximum current (kA)	200	150	100	100
Minimum current (kA)	3	5	10	16

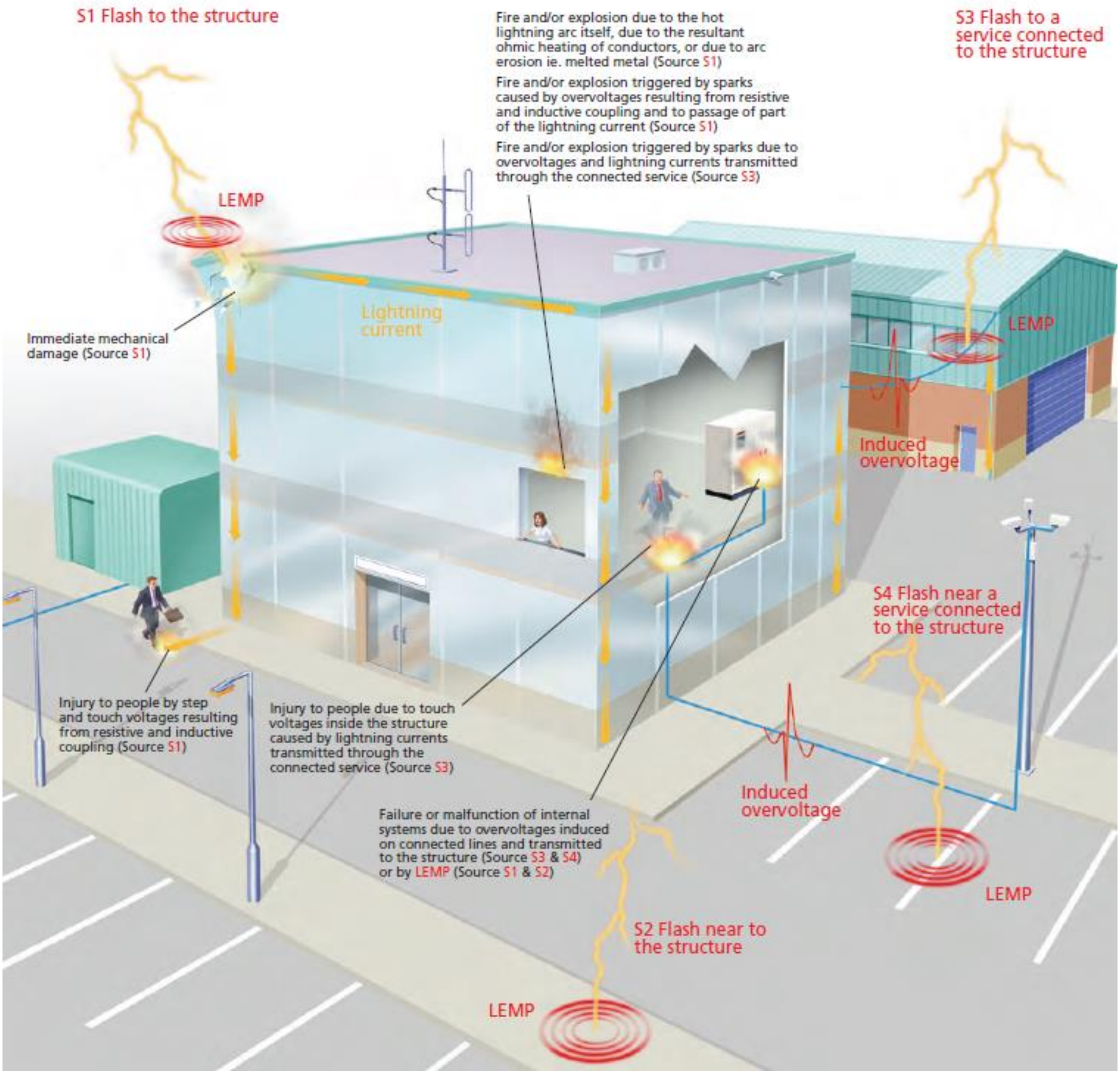


Figure 3. 2 The types of damage and loss resulting from a lightning strike on or near a structure

3.3.4 Lightning Protection Zones (LPZ)

The general principle is that the protection-requiring equipment should be placed in an LPZ whose electromagnetic characteristics are consistent with the stress of the equipment or immunity capability. The definition supports external areas with a risk of direct lightning stroke (LPZ 0_A) or a risk of a partial lightning current occurring (LPZ 0_B) and safety rates inside internal zones (LPZ 1 & LPZ 2). In general, the higher the zone number (LPZ 2; LPZ 3, etc.), the lower the predicted electromagnetic effects.

Usually, any sensitive electronic equipment should be located in higher-numbered LPZs and protected by appropriate surge protection measures against Lightning Electromagnetic Impulse (LEMP).

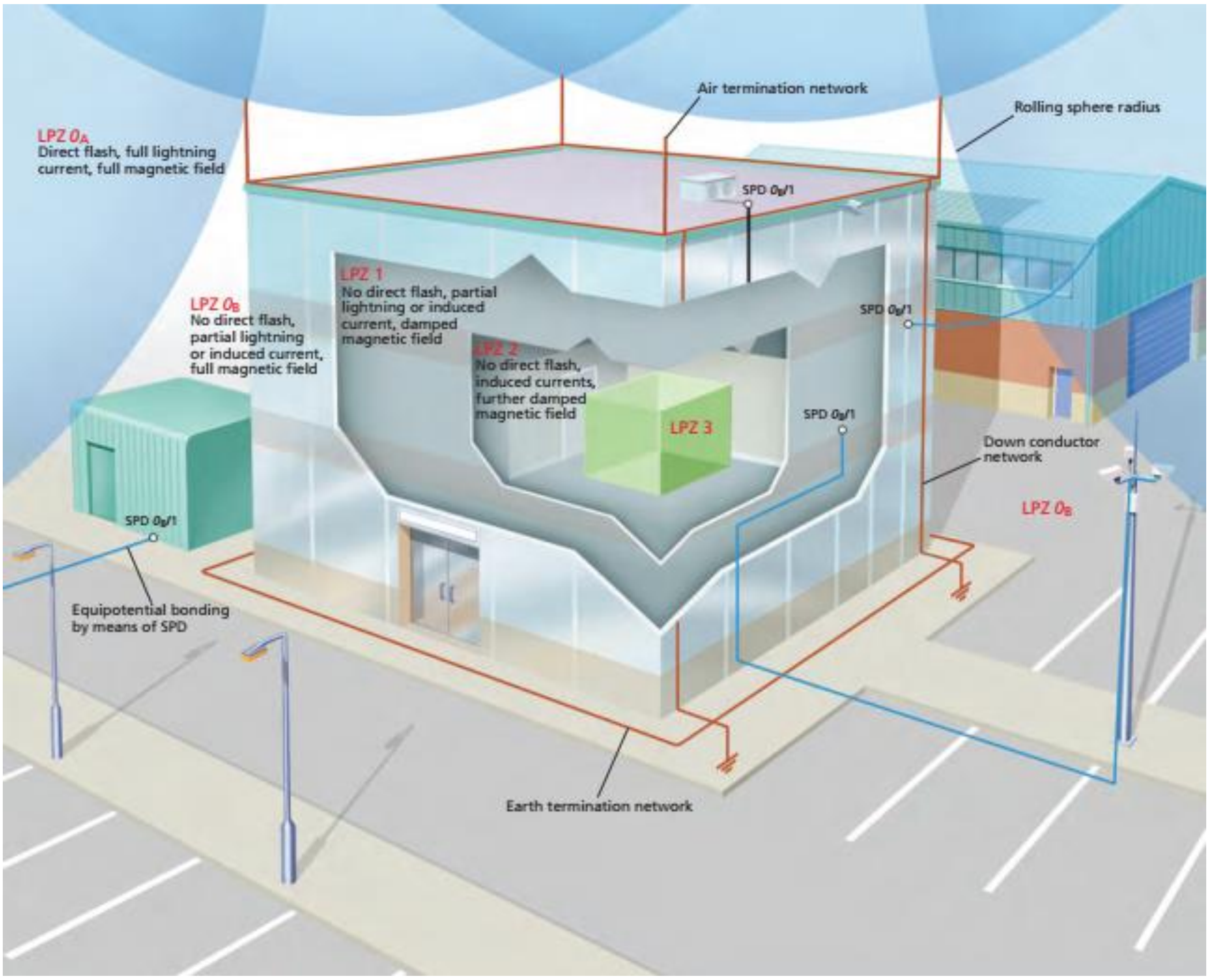


Figure 3. 3 Graphical representation of LPZ concept

3.4 RISK MANAGEMENT

The first stage of the risk assessment determines which of the four types of losses (as defined in BS EN / IEC 62305-1) the system will incur and its contents. The final goal of the risk assessment is to measure the related primary risks and, if possible, reduce them.

- R1-Risk of loss of human life
- R2-Risk of loss of service to the public
- R3-Risk of loss of cultural heritage
- R4-Risk of loss of economic value

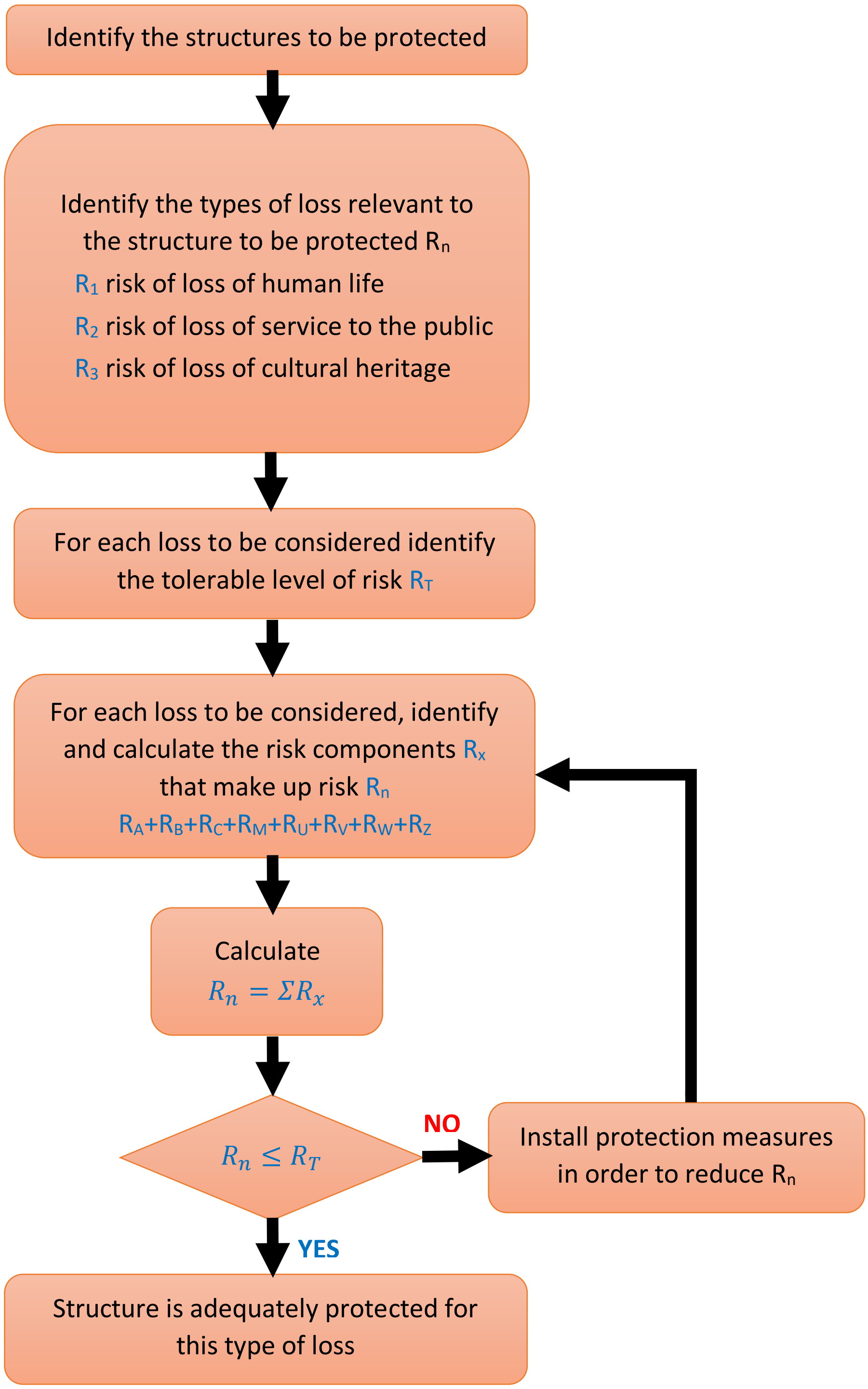


Figure 3. 4 Procedure for deciding the need for protection

A tolerable risk (R_T) is set for each of the first three primary risks. Actual risk (R_n), as specified in the standard, is calculated through a long series of calculations. In the case of actual risk (R_n) is less than or equal to the tolerable risk (R_T), then there is no need for protection measures. If the actual risk (R_n) is greater than the corresponding tolerable risk (R_T), it is necessary to take protective measures.

The above process is repeated until Rn is less than or equal to its corresponding RT (By using new values that relates to the chosen protection measures). This is an iterative process, as shown in Figure 2.4 above, that decides what the choice of Lightning Protection Level (LPL) for the Lightning Protection System (LPS) is and what Surge Protective Measures (SPM) should be taken to counter Lightning Electromagnetic Impulse (LEMP).

3.5 PHYSICAL DAMAGE TO STRUCTURES AND LIFE HAZARD

3.5.1 Lightning Protection System (LPS)

BS EN / IEC 62305-1 defined four levels of lightning protection (LPLs) based on the probable minimum and maximum lightning currents. These LPLs directly equate with Lightning Protection System (LPS) classes.

Table 3. 3 Relation between Lightning Protection Level (LPL) and Class of LPS

LPL	Class of LPS
I	I
II	II
III	III
IV	IV

3.5.2 External LPS design considerations

Initially, the lightning protection designer must consider the thermal and explosive effects caused at the point of the lightning strike and the consequences for the structure under consideration. Depending on the consequences, the designer may choose one of the following types of external LPS given below.

- Isolated- This LPS is typically chosen when the structure is constructed of combustible materials or presents a risk of explosion
- Non-isolated - Non-isolated systems can be fitted or cases where no such danger exists.

➢ External LPS may consist of the following,
  - Air termination system
  - Down conductor system
  - Earth termination system

Individual elements of an LPS should be linked using correct lightning protection components (LPC), which comply with the BS EN 50164 series (in the case of BS EN 62305). This will ensure, in the event of a lightning current discharge to the structure, the proper design and choice of components minimize any potential damage.

3.5.3 Air termination system

The air termination system's function is to catch the current of lightning discharge and harmlessly dissipate it to earth via a down conductor and earth termination system. Hence the use of a properly designed air termination device is essential. BS EN / IEC 62305-3 advocates the following for the design of an air termination in any combination:

- Air rods (or finials) whether they are free-standing masts or linked with conductors to form a mesh on the roof
- Catenary (or suspended) conductors, whether they are supported by free-standing masts or linked with conductors to form a mesh on the roof
- A network of meshed conductors which may be in direct contact with or suspended above the roof (if it is of paramount importance that the roof is not exposed to direct light discharge)

The standard makes it quite clear that the positioning requirements set out in the standard must be met by all types of air termination systems employed. It highlights the need to install the air termination components at the corners, exposed points, and edges of the structure. The three primary methods recommended for determining the position of the air termination systems are:

- The rolling sphere method
- The protective angle method
- The mesh method

3.6 ROLLING SPHERE METHOD

The rolling sphere method is a simple way to identify areas of a structure that require protection, taking into consideration the likelihood of side strikes to the structure. This method is suitable for defining protection zones for all types of structures, particularly those with complex geometries. The concept of applying the rolling sphere to a structure is illustrated in Figure 3.5

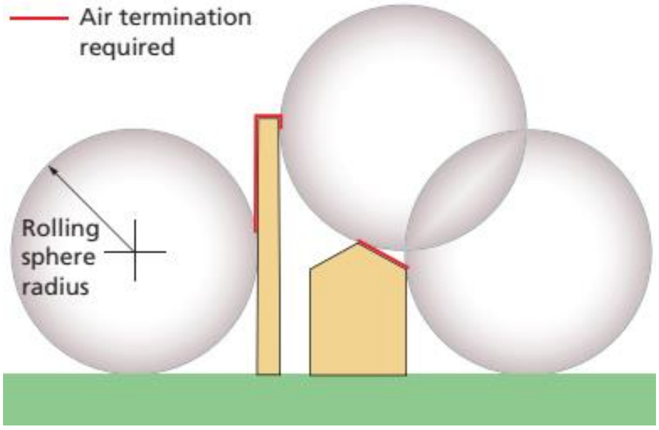


Figure 3. 5 Application of the rolling sphere method

The rolling sphere method was used in BS 6651, the only difference being that in BS EN/IEC 62305, there are different radii of the rolling sphere that correspond to the relevant class of LPS.

Table 3. 4 **Maximum values of rolling sphere radius corresponding to the Class of LPS**

Class of LPS	Rolling sphere radius (m)
I	20
II	30
III	45
IV	60

The charge stored in the lightning and the sphere radius for the RSM is calculated by using the flowing formulas,

1. Charge / (C)

   $$Q = 0.061I$$

   Ex: For 30kA surge current, $Q = 1.8C$

2. Striking distance (radius of Rolling Sphere Method) / (m)

   $R_s = 10I^{0.65}$

   Ex: For 30kA surge current, $R_s = 91.2m$

3.7 PROTECTIVE ANGLE METHOD

The protective angle method is a mathematical simplification of the rolling sphere method. Protective angle (α) is the angle created between the tip 'A' of the vertical rod and a line projected down to the surface on which the rod sits as seen on figure 3.6

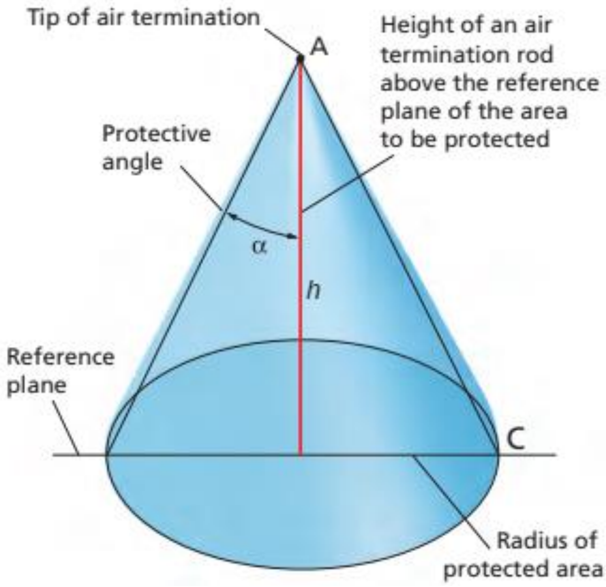


Figure 3. 6 The protective angle method for a single air rod

The air rod's protective angle is a three-dimensional term whereby the rod is given a protective cone by sweeping the line 'AC' around the air rod at the protective angle a full 360 degrees. The protective angle varies with the different air rod height and LPS level. The protective angle for an air rod is determined from IEC/BS EN 62305-3 as shown in Figure 3.7

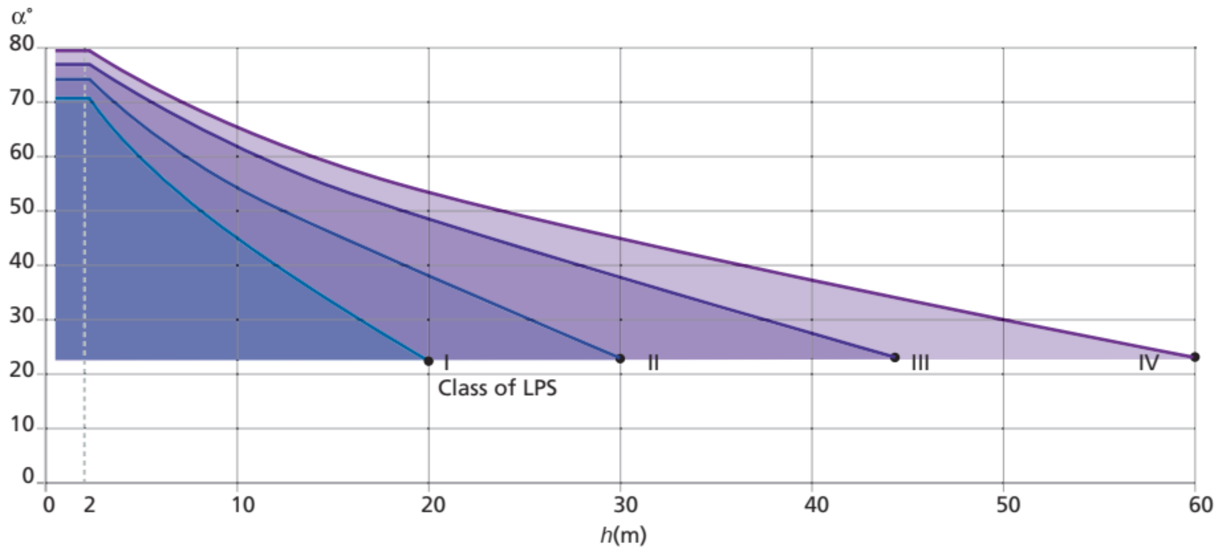


Figure 3. 7 Determination of the protective angle

Note 1- Not applicable beyond the values marked with ●
Only rolling sphere and mesh methods apply in these cases

Note 2- h is the height of air-termination above the reference plane of the area to be protected

Note 3 -The angle will not change for values of h below 2m

Varying the protection angle is a change to the simple 45º zone of protection afforded in most cases in BS 6651. Furthermore, the new standard uses the height of the air termination system above the reference plane, whether that be ground or roof level (See Figure 3.8). For any shaped buildings, the protective angle procedure is suitable. Nevertheless, this method is applicable only up to a height equal to that of the appropriate LPL's rolling sphere radius.

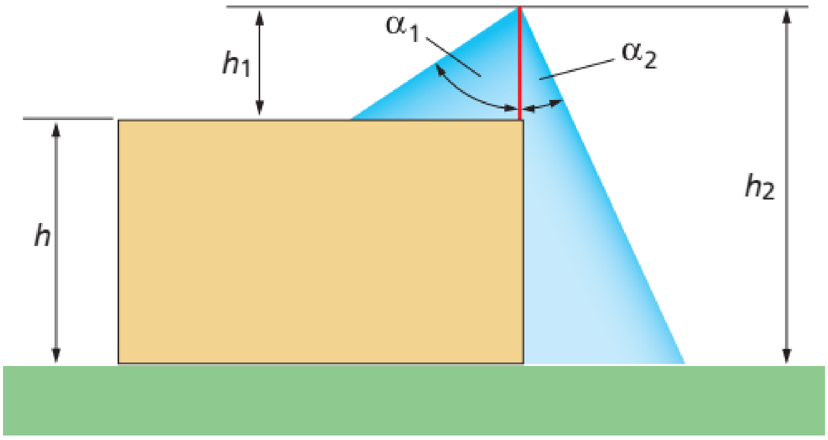


Figure 3. 8 Effect of the height of the reference plane on the protection angle

3.8 MESH METHOD

This was the most widely used method by using BS 6651 guidelines. Four different air termination mesh sizes are defined within BS EN / IEC 62305 and correspond to the relevant LPS class (see Table 3.5). Modern research into the damage inflicted by lightning has shown that the edges and corners of roofs are most vulnerable to damage. Thus, perimeter conductors should be installed on all structures, especially with flat roofs, as close to the outer edges of the roof as possible.

Table 3. 5 Maximum values of the mesh size corresponding to the Class of LPS

Class of LPS	Mesh size (m)
I	5 x 5
II	10 x 10
III	15 x 15
IV	20 x 20

This approach is suitable where plain surfaces require protection when the following conditions are fulfilled:

- Air termination conductors shall be placed on roof edges, roof overhangs and roof ridges with a pitch above 1 in 10 (5.7 degrees)
- No metal installation extends beyond the air termination system
-

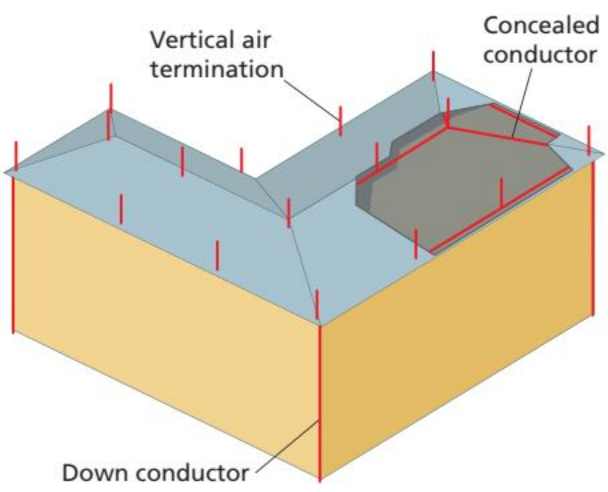


Figure 3. 9 Concealed air termination network

The air rods should be spaced no more than 10 m apart, and if strike plates are used as an alternative, they should be positioned strategically not more than 5 m apart above the roof area.

3.9 ELECTRICAL AND ELECTRONIC SYSTEMS WITHIN THE STRUCTURE

In this section of the standard, the protection of electrical and electronic systems in a structure is discussed by defining lightning protection zones.

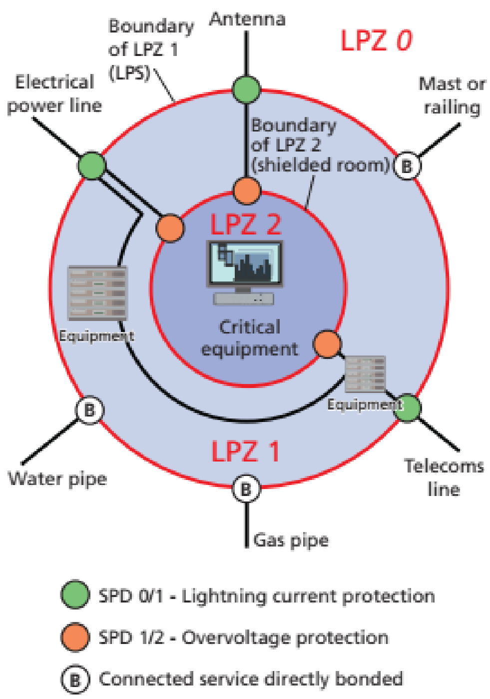


Figure 3. 10 Basic LPZ concept

A series of LPZs are generated within a system to have gradually less exposure to the effects of lightning, or identified as having it already. Successive zones use a mix of bonding, shielding, and integrated SPDs to achieve a significant reduction in LEMP frequency, as well as radiated magnetic field effects from conducted surge currents and transient over voltages. Designers design these levels so that the more sensitive devices are placed in more protected zones. The LPZs can be divided into two categories.

1. external (LPZ 0A, LPZ 0B)
2. internal (LPZ 1, 2) zones.

3.9.1 External zones

- LPZ O_A is the area that subjects to direct lightning strikes. Therefore, it may need to carry the full lightning current. Usually, this is the roof area of a building. Full electromagnetic field occurs in this region.
- LPZ O_B is an area that is not subject to direct lightning strokes and is typically the sidewall of the structure. However, the maximum electromagnetic field also exists here, and it is possible to have partial lightning currents and switching surges.

3.9.2 Internal zones

LPZ 1 is the internal area that is subject to partial lightning currents. The conducted lightning currents are reduced compared with the external zones. Typically, this is the area in which services enter the structure or where the main power switchboard is located. LPZ 2 is an internal area further inside the structure, where the remaining of the lightning impulse currents is reduced compared to LPZ 1.

This is typically a screened room, or at the sub-distribution board area for mains power. Protection levels must be coordinated within a zone with the immunity characteristics of the equipment to be covered.

3.9.3 Surge protection measures (SPM)

Correct installation of coordinated Surge Protective Devices protects equipment from damage, as well as ensures continuity of its operation, which may be critical for eliminating downtime. Appropriate SPDs (Coordinated SPDs or Enhanced SPDs) should be fitted wherever services cross from one LPZ to another.

3.10 MODIFIED ROLLING SPHERE METHOD

The main drawback of the rolling sphere method is that it disregards the upward leader development and assumes the same probability for attachment to the ground, to a structure, and an LPS. The modified rolling sphere method is based on physical phenomena leading to the formation and the development of positive upward leaders in the field produced by the negative downward leader charge distribution and by some other competing upward leaders. Its purpose is to develop a 3-D numerical model to improve the interception efficiency of the Lightning Protection System.

It has demonstrated that the numerical model goes farther than the Rolling Sphere Method and considers the effect of competing upward leader emitted from the lightning protection system and vulnerable zones on the structure, like edges or corners.

3.10.1 Modified Striking Distance (rms)

The striking distance of tower-like objects is redefined as the distance to the upper end of the upward connecting leader at the time when the standard streamer zone of the downward and upward connecting leaders is formed. New striking distance is almost independent of the height of the rod and varies with the lightning current.

$$r_{ms} = 4.2I^{2/3}$$

With RMS the modified striking distance (m) and I the lightning current (kA)

3.10.2 Lateral Protection Distance (D_p)

The maximum distance between the axis of the downward leader origin and the lightning rod, from which there is a systematic failure of the capture by the LPS.

$$D_P = 3h^{0.3}I^{2/3}$$

With: h the height of the rod (m) and I the lightning current(kA).

3.10.3 Upward Connecting Leader Effects

The upward connecting leader emitted from a lightning rod, in the form a cone of radius L_{up} (m) and height H_{up}(m)

$$L_{up} = \frac{(0.054hI - 0.178h + 0.124I + 1.057)}{3.02 - 0.19h}$$

$$H_{up} = 0.054hI + 0.87h + 0.124I + 0.37$$

With: h the height of the lightning rod (m) and I the lightning current (kA).

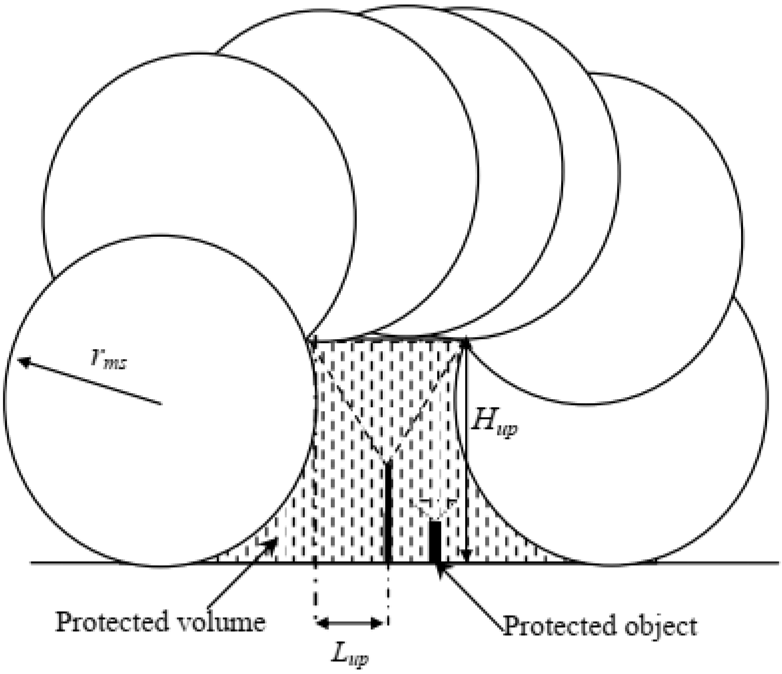


Figure 3. 11 Modified rolling sphere method

3.11 ELECTROSTATIC DISCHARGE MODELLING

Electrostatic discharge is the flow of electricity between electrically charged objects. This occurs when differently charged objects are brought close together, or the dielectric medium between them breaks down, creating a spark. Lightning is also a large-scale electrostatic discharge event. The finite element method is the most common method used in solving mathematical models (in this case, the electrostatic discharge model) governed by partial differential equations, and electric field data can be obtained.

3.11.1 Finite Element Method

The idea of the finite element method is to break the problem down into a large number of regions, each with simple geometry. This process is called discretization. In general, triangular elements are used through the discretization process. The real solution for the desired potential is approximated by straightforward function using boundary conditions, known potentials, and material properties, after breaking the insulating region down into triangles. In the form of a sparse matrix, the approximation functions are written for each triangle to constitute a linear equation system. This linear system is solved by a numerical method iteratively, and potentials at the nodes of each triangle are calculated. After that, potential approximation functions are formed. Following this method, it is possible to determine electric potential and electric field strength of any point concerning potential magnitudes at the triangle's corners.

3.11.2 Glow corona discharge

Figure 3. 12 Glow corona on a transmission line

Due to the electric field of thunder clouds, glow corona discharges occur from the tip of tall slim grounded objects like lightning rods. These discharges can generate positive ions, which could shield the geometric electric field and disturb upward leader development before a lightning strike. Based on this fact, there are different non-conventional lightning protection systems such as the dissipation array system, which is shown in Fig 3.13 that can prevent lightning strikes to objects protected by such systems. Further, there are lightning rods specially designed to avoid glow corona generation, which claims to be more efficient than conventional lightning rods.

Figure 3. 13 Dissipation array system

CHAPTER 4
DEVELOPMENT OF 3D MODELS

4.1 INTRODUCTION

The 3D models are developed using the specifications obtained for the stupa structures, and the CAD design process was done with the help of Solid works and COMSOL Multiphysics engine. The analysis of the structures was performed using these 3D models.

4.2 DEVELOPMENT OF 3D MODELS FOR THE STUPA STRUCTURES

There were four main stupa structures and palace designed in this part of the modeling,

They are,

1. Ruwanweliseya
2. Abayagiriya
3. Jethawanaramaya
4. Mirisavetiya

4.3 SPECIFICATIONS OF THE STUPA STRUCTURES

The dimensions of the stupa structures are shown in table 1.1. The 3D models are developed according to these specifications.

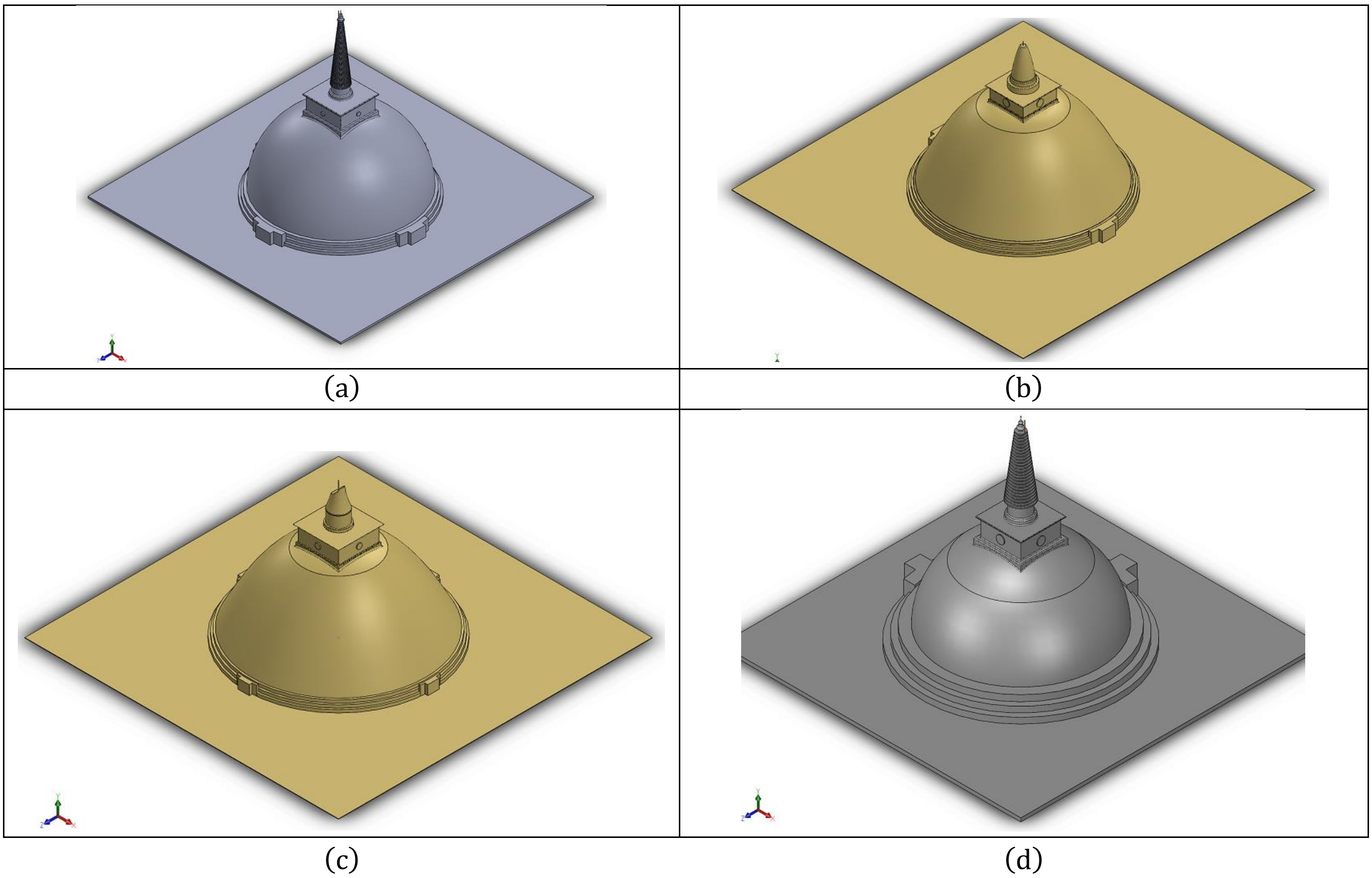
Table 4. 1 DIMENSION OF THE STUPA STRUCTURES

Dimensions	Ruwanweliseya	Abayagiriya	Jethawanaramaya	Mirisavetiya
King	Dutugemunu	Valagambahu	Mahasen	Dutugemunu
Period	161-137 BC	88-76 BC	269-296 AD	161-137 BC
Shape	Bubble	Paddy heap	Paddy heap	Bubble
Photo (present)				
Location coordinates				
Longitudes E	80.3942	80.3931	80.4015	80.3868
Latitude N	8.3500	8.3709	8.3515	8.3450
Basal rings (1,2,3)				
Radius [m]	41.9	50.9	53.05	27.0
Height [m]	4.9	4.9	5.2	4.0
Dome (4)				
Radius [m]	38.6	47.3	50	21.5
Height from Basal rings [m]	38.4	42.4	41.8	20.4
Square chamber (5)				
Half-width [m]	9.4	11.1	11.6	
Height [m]	7.9	8.2	8.8	6.1
Cylinder (6)				
Radius [m]	3.8	4.4	5.2	
Height [m]	3.9	4.9	7.6	4.0
Spire (7)				
Radius [m]	4.5	5.2	5.5	

Present Height [m]	32.9	16.3	7.3	
Ancient height	32.9	29.6	30.8	
Mineral (8,9)				
Radius [m]	0.9	0.9		
Height [m]	4.3	6.1		
Present height [m]	92.4	74.7	70.7	54.6
Present radius [m]	41.9	50.9	53.05	27.0
Ancient height [m]	92	106.7	122	61
Ancient radius [m]	45.2	54.5	56.5	25.5
Base floor				
Shape	Square	Square	Square	Square
half Width/radius [m]	73	97.5	90	41.5

4.4 3D MODELS OF THE PRESENT STUPA STRUCTURES DEVELOPED USING SOLIDWORKS

The following 3D models were developed using SOLIDWORKS. The models are generated such that they consist of complex geometrical characteristics present on the real stupa structure while considering the actual dimensions in the present conditions.

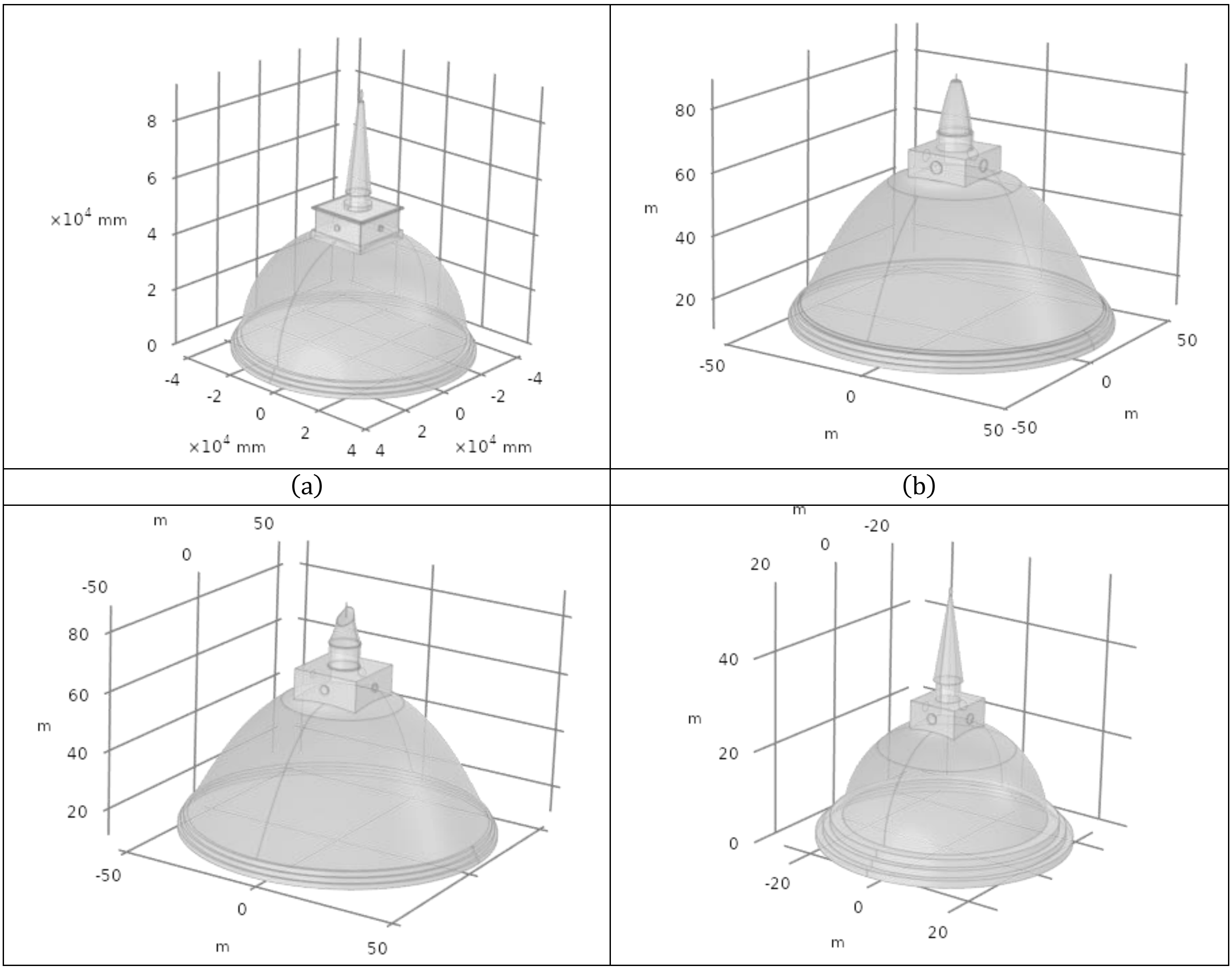


(a) (b) (c) (d)

Figure 4. 1 SOLIDWORKS model of the present (a)Ruwanweliseya, (b)Abayagiriya, (c)Jethawanaya, (d)Mirisavetiya

4.5 3D MODELS OF THE PRESENT STUPA STRUCTURES DEVELOPED USING COMSOL

The following 3D models were developed using COMSOL Multiphysics engine



(a) (b)

(c) (d)

Figure 4. 2 COMSOL model of the present (a) Ruwanweliseya, (b)Abayagiriya, (c) Jethawanaya, (d)Mirisavetiya

CHAPTER 5
RISK ANALYSIS FOR INDIVIDUAL STUPA STRUCTURES

5.1 INTRODUCTION

For the developed 3D models, the risk analysis for the structure and the people near vicinity were performed using the following methods

1. IEC62305 Based risk factor analysis
2. By using the protective angle method
3. By using the rolling sphere method
4. By using the modified rolling sphere method
5. By using electric field distribution

5.2 IEC62305 BASED RISK FACTORS

Risk analysis provides an estimation of vulnerabilities of the structure during the lightning strike so that protective measures can be taken to avoid damages.

- **Risk of loss of cultural heritage (R_3)**

$$R_3 = R_{B3} + \mathrm{R}_{\mathrm{v3}}$$

Table 5. 2 Source and the type of damage selection

RX	**Source of damage**	**Type of damage**
RB	Flashes to the structure (S1)	Physical damage caused by dangerous sparking inside the structure (D2)
RV	Flashes to a service line connected to the structure (S3)	Physical damage caused by dangerous sparking inside the structure (D2)

Since there are no service lines connected to the stupa, only R_B is considered.

$$R_3 = N_D P_B L_B$$

N_D is the expected annual number of dangerous events.

$$N_D = N_G A_D C_D \times 10^{-6}$$

Where,

C_D - location factor

N_G is the flash density in strikes to ground per square kilometer per year, and it can be approximated for temperate regions using the following formula.

$$N_G \approx 0.1 \times T_D$$

T_D is the number of thunderstorm days per year.

A_D is the collection area of the structure. For structures of a more complex shape, it may be necessary to determine the collection area graphically or by the use of computer software. For complex structures with outer segments, the following equation can be used. Typically, the following is used although this is used in some cases

$$A_D = \pi \times (3 \times H_P)^2$$

or

Circle of radius 3H

Where,

H - the height of the stupa

H_p - height with protrusion.

P_B - the probability of physical damage to a structure.

The loss caused by physical damage can be calculated using,

$$L_B = \frac{r_P r_f L_f c_z}{c_t}$$

r_p is the factor reducing loss due to physical damage depending on the measures taken to reduce the consequences of the fire

r_f is the factor reducing loss due to physical damage depending on the risk of fire

L_F indicates the loss due to physical damage

$\frac{c_z}{c_t}$ is the ratio of cultural heritage in the zone to the total value of the structure

5.3 BY USING PROTECTIVE ANGLE METHOD

This method is also known as geometrical modeling. The analysis performed for each of the stupa structures are shown in the following subsections.

5.3.1 RUWANWELISEYA

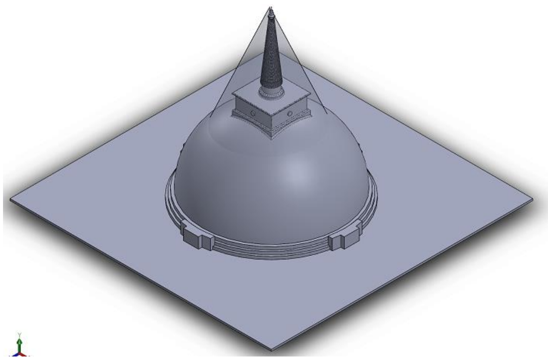


Figure 5. 1 Protective angle method applied to Ruwanweliseya stupa

5.3.2 ABAYAGIRIYA

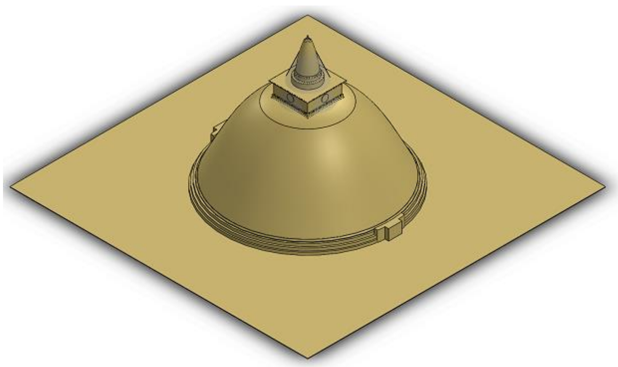


Figure 5. 2 Protective angle method applied to Abayagiriya stupa

5.3.3 JETHAWANARAMAYA

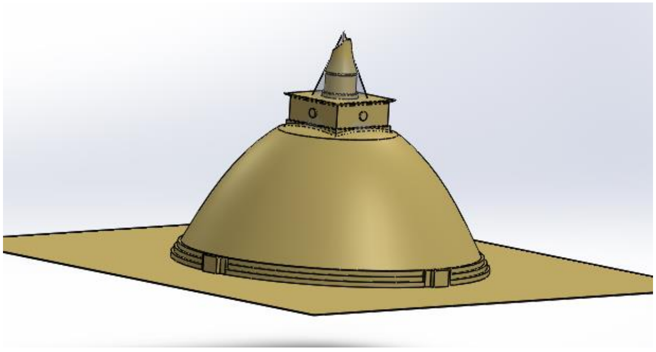


Figure 5. 3 Protective angle method applied to Jethawanaramaya stupa

5.3.4 MIRISAVETIYA

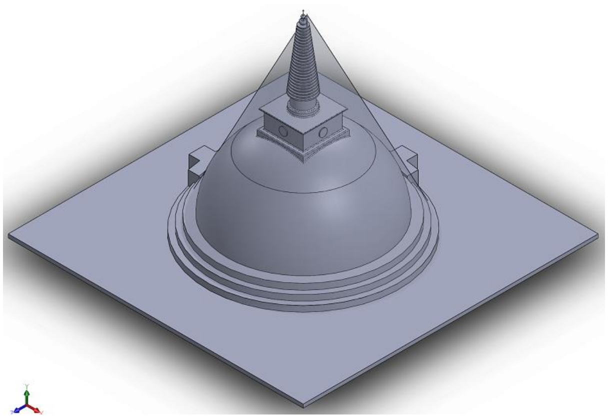


Figure 5. 4 Protective angle method applied to Mirisavetiya stupa

By observing the above stupa structures, it can be seen that only Mirisavetiya stupa $(26.4°)$ is protected under level 4 protective angle method according to the IEC62305 standard. Since other stupa structures are higher than 60m, this method is not applicable.

5.4 ROLLING SPHERE METHOD

This method is also known as the electro geometrical model. The analysis performed for each of the stupa structures are shown in the following subsections. The regions with the lightning risk are also shown in the following figures.

5.4.1 RUWANWEISEYA

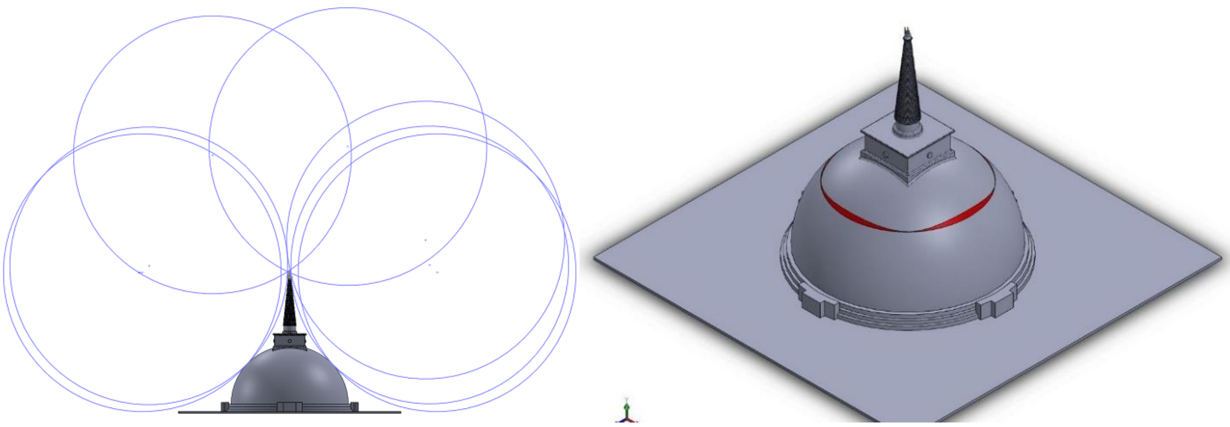


Figure 5. 5 Unprotected regions obtained from Rolling sphere method- Ruwanweliseya stupa

5.4.2 ABAYAGIRIYA

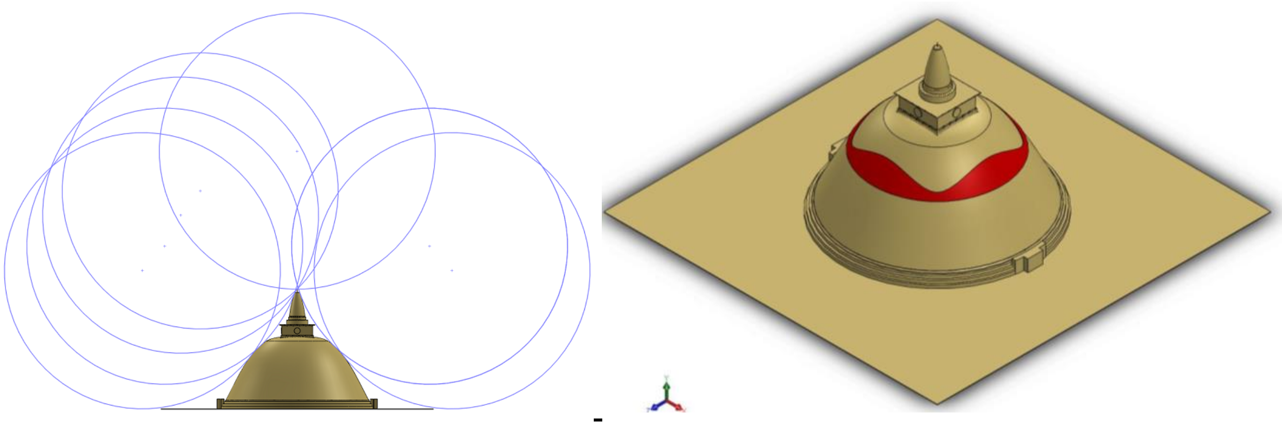


Figure 5. 6 Unprotected regions obtained from Rolling sphere method- Abayagiriya stupa

5.4.3 JETHAWANARAMAYA

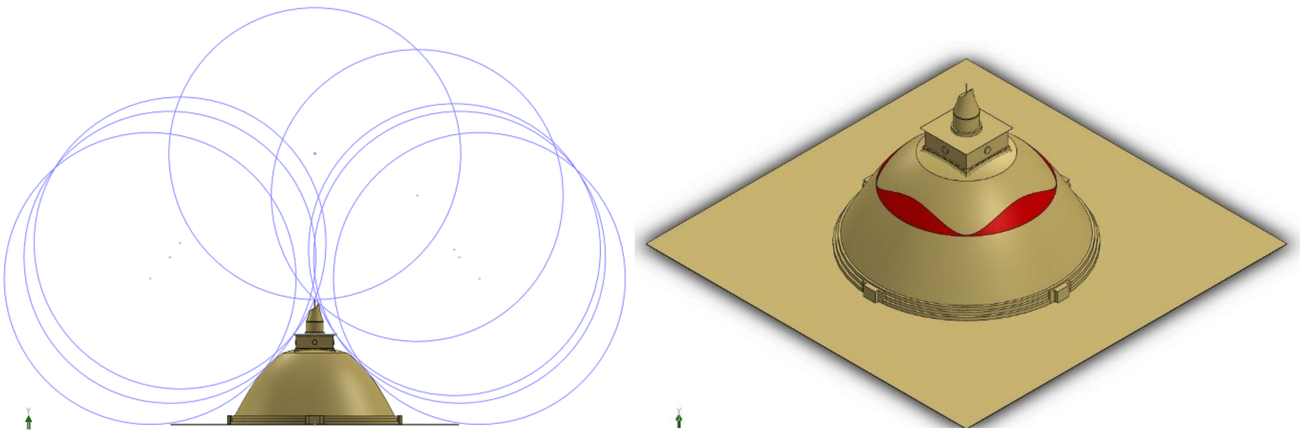


Figure 5. 7 Unprotected regions obtained from Rolling sphere method- Jethawanaramaya stupa

5.4.4 MIRISAVETIYA

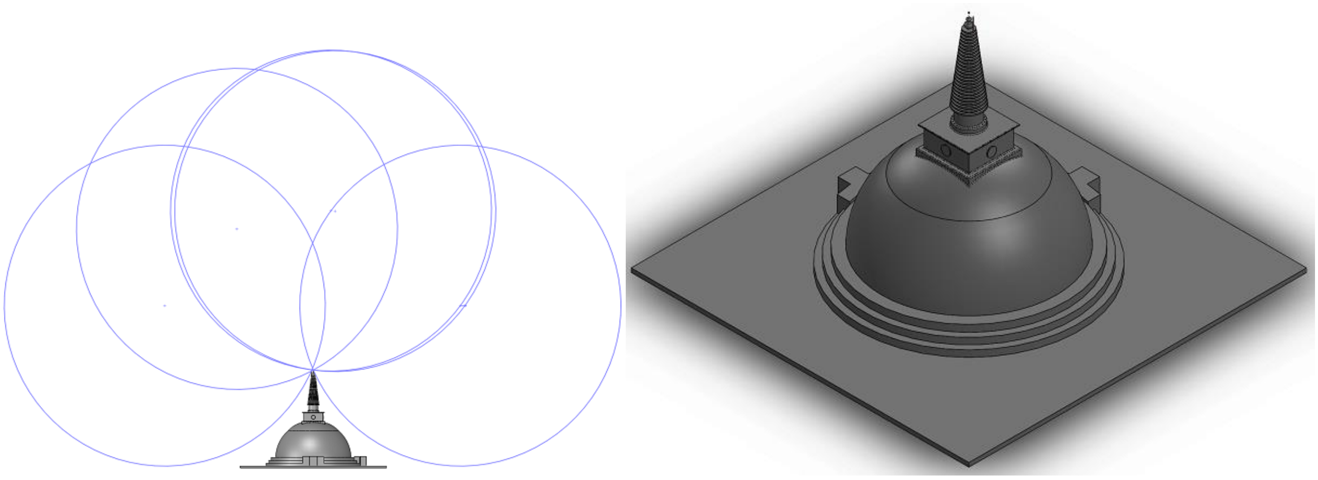


Figure 5. 8 Unprotected regions obtained from Rolling sphere method- Mirisavetiya stupa

Based on the analysis of the present and ancient stupa structures, red-colored areas are vulnerable to lightning strikes. The protective copper flat strip can be implemented along the unprotected regions to ensure the protection of the stupa structures.

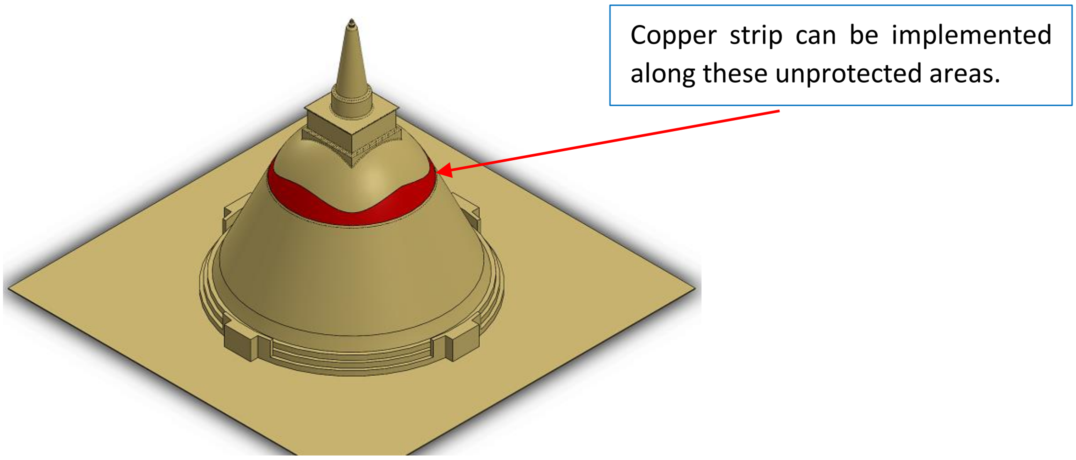


Figure 5. 9 Implementation of copper mesh

5.5 MODIFIED ROLLING SPHERE METHOD

Although the modified rolling sphere method is not included in the lightning standards, it can be used to determine the protective regions while considering the upward leader generation in the stupa structure. The upward cone dimensions can be calculated as follows

Cone radius $L_{up} = \frac{0.054hI - 0.178h + 0.124l + 1.057}{3.02 - 0.19h}$

Cone height $H_{up} = 0.054hl + 0.87h + 0.124l + 0.37$

Where,

h - Height of the lightning rod(m)

I - Lightning current(kA)

5.5.1 RUWANWELISEYA

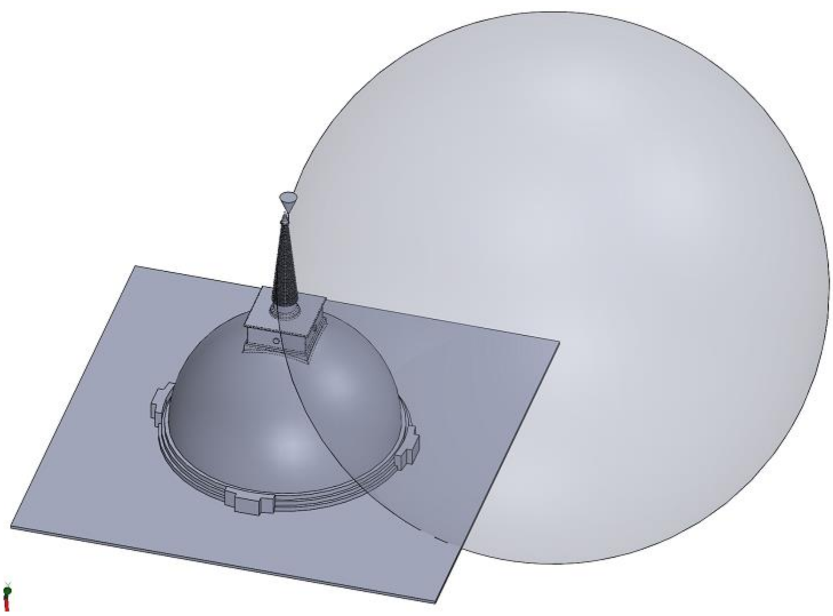


Figure 5. 10 Modified Rolling sphere method application to Ruwanweliseya stupa

5.5.2 ABAYAGIRIYA

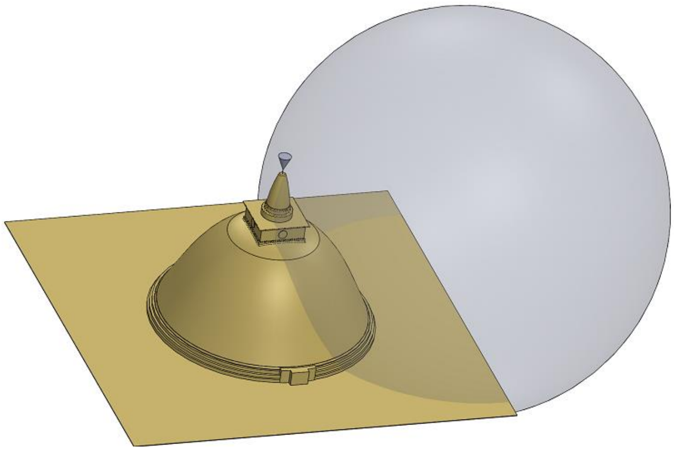


Figure 5. 11 Modified Rolling sphere method application to Abayagiriya stupa

5.5.3 JETHAWANARAMAYA

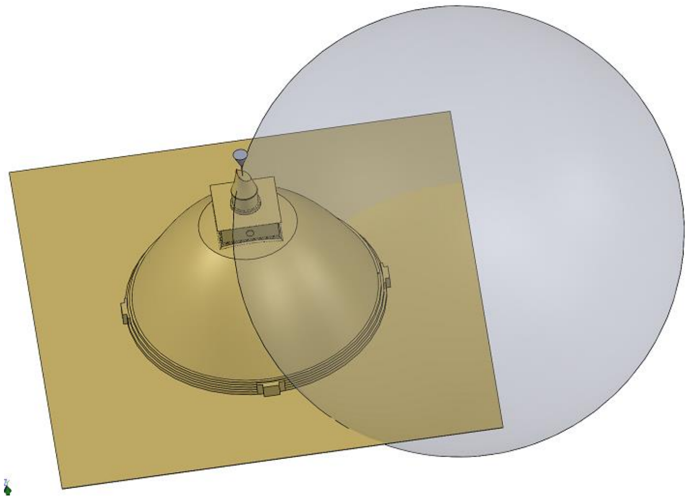


Figure 5. 12 Modified Rolling sphere method application to Jethawanaramaya stupa

5.5.4 MIRISAVETIYA

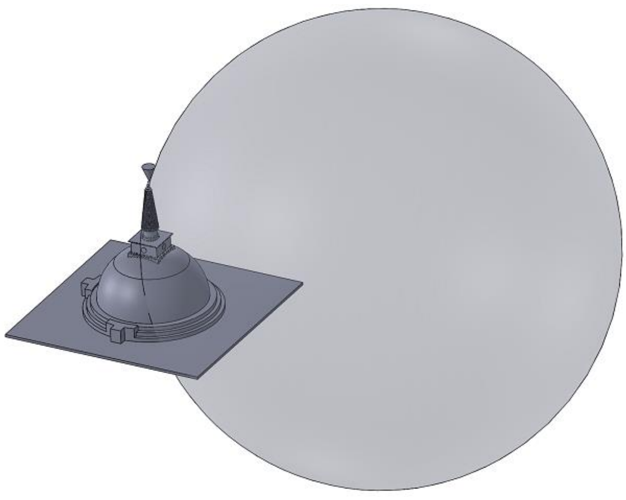


Figure 5. 13 Modified Rolling sphere method application to Mirisavetiya stupa

Based on the analysis of the present stupa structures, they are protected according to the modified rolling sphere method.

5.6 ANALYSIS USING ELECTRIC FIELD DISTRIBUTION (USING COMSOL)

The physical properties related to the material (e.g., stupa material. Surrounding air) are considered for the modeling purposes. This allows the in-depth analysis of the charge distribution on the stupa structure, which ultimately results in the upward leader generation. For this modeling purpose, a line charge is modeled with the COMSOL interface that acts like lightning, which induces electrical field on the stupa structure.

This induced electrical field causes the charge density along the stupa structure to vary If the charge density goes over a certain amount. We can conclude that it is the point where the upward leader is generated. Initially, the lightning surge is modeled in steps until the charge distribution exceeds 300kA/m. For the analysis of the physics model, a 3d mesh was created around the stupa structure, exceeding up to the cloud surface (which was taken as 2km above from the ground) as shown in figure 5.17 and figure 5.18

Figure 5. 14 Mesh network built for the stupa structure

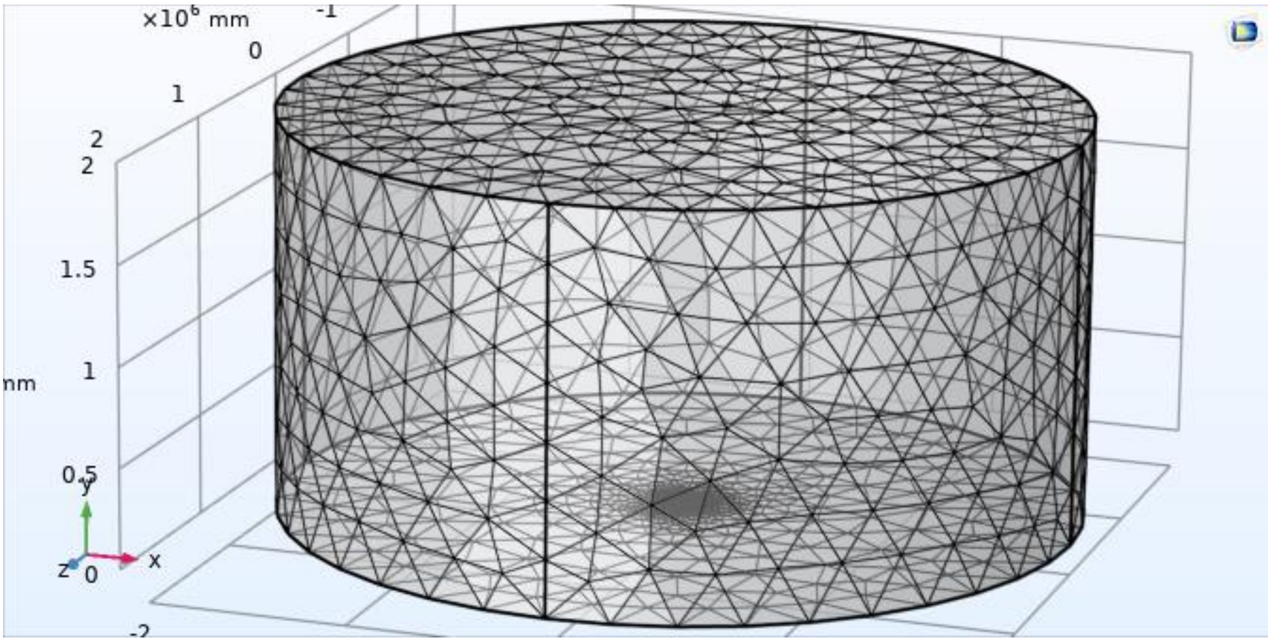


Figure 5. 15 Mesh network around the stupa structure

Then a line charge of -1.8C/m has created that initiate from the cloud surface and towards the stupa structure, which is shown in figure 5.18 below. For each of the testing, leader steps of 50m until the tip of the downward leader reach the location of the center of the RSM method sphere.

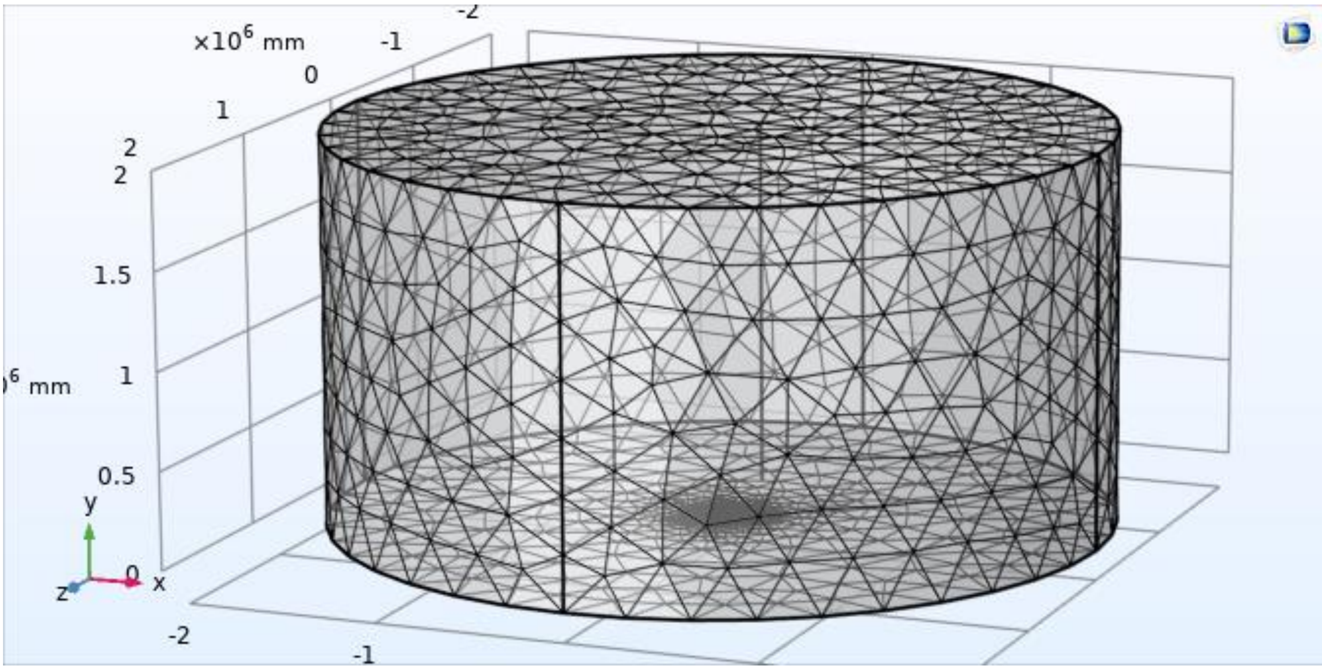


Figure 5. 16 Mesh network with line charge present

Case studies were performed for each of the stupa considering

- A typical case of 30kA surge
- Worse case of 200kA surge

And for each of the cases, the lightning effect was studied when,

- The surge is directly above the stupa tip
- When the surge is at the corner of the stupa with a downward leader tip is at the center of the RSM sphere

The case studies and the results are shown in the next chapters.

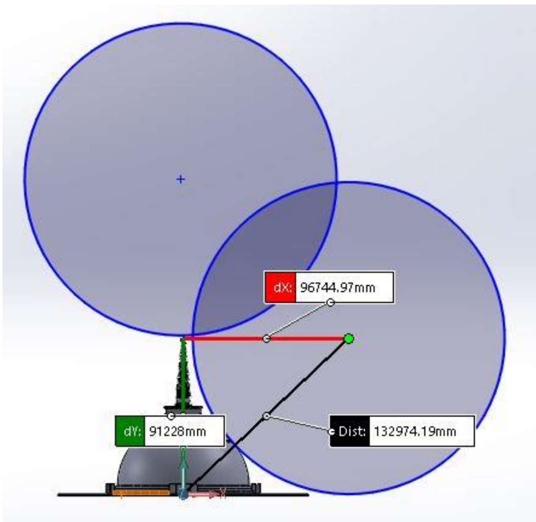


Figure 5. 17 Directly above and side downward leader locations

5.6.1 Ruwanweliseya at present dimensions

5.6.1.1 Considering 30kA surge

- **When the surge is directly above the stupa**

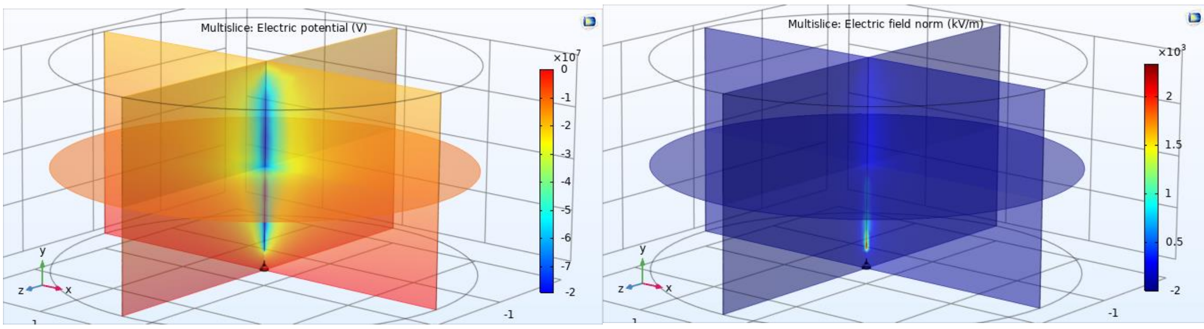


Figure 5. 18 (a) Voltage distribution for Ruwanweliseya-30kA- Directly above at 91.2m from the tip (b)Electric field distribution for Ruwanweliseya-30kA- Directly above at 91.2m from tip

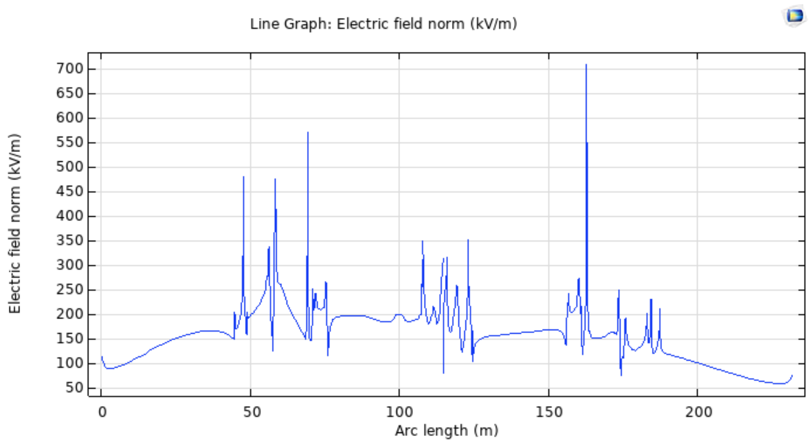


Figure 5. 19 Electric field distribution along cross-section Ruwanweliseya-30kA- Directly above at 91.2m from tip

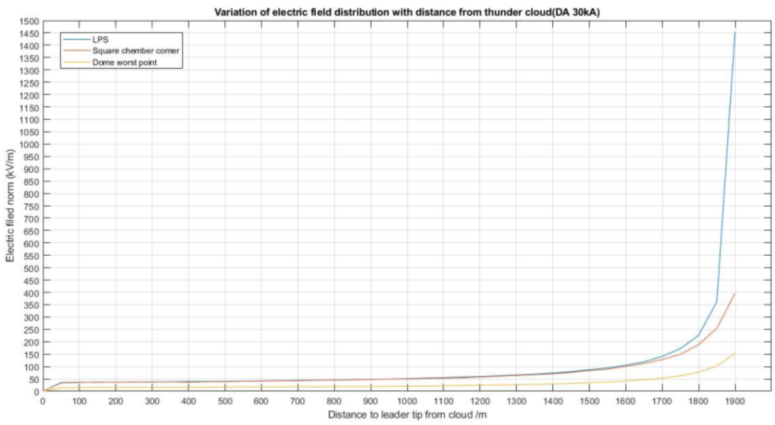


Figure 5. 20 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 19, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will not initiate. Also, for the cases of square chamber and dome worst point, which is the unprotected region obtained from RSM, as shown in figure 5.5, an upward leader will not initiate from those points. So, it can be concluded that for any point of the stupa, an upward leader will not initiate.

- **When the surge is on the side of the stupa**

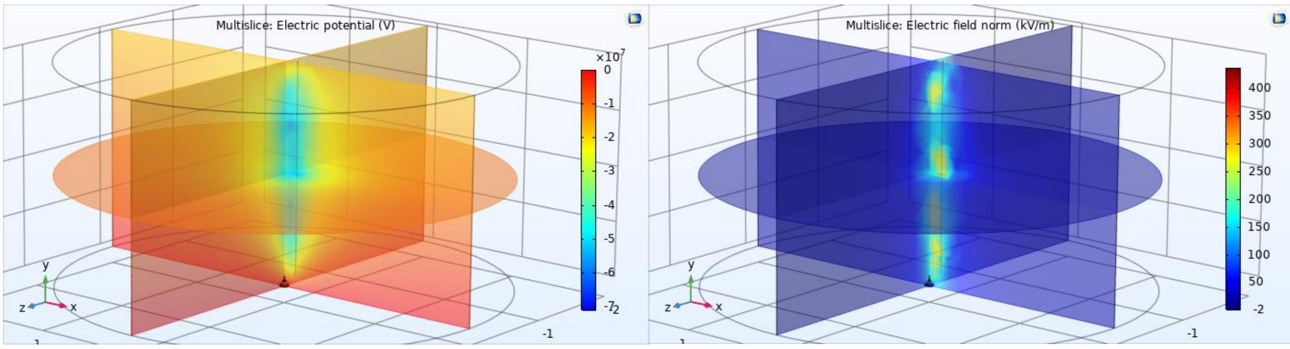


Figure 5. 21 (a) Voltage distribution for Ruwanweliseya-30kA- Directly above at 91.2m from ground
(b) Electric field distribution for Ruwanweliseya-30kA- Directly above at 91.2m from ground

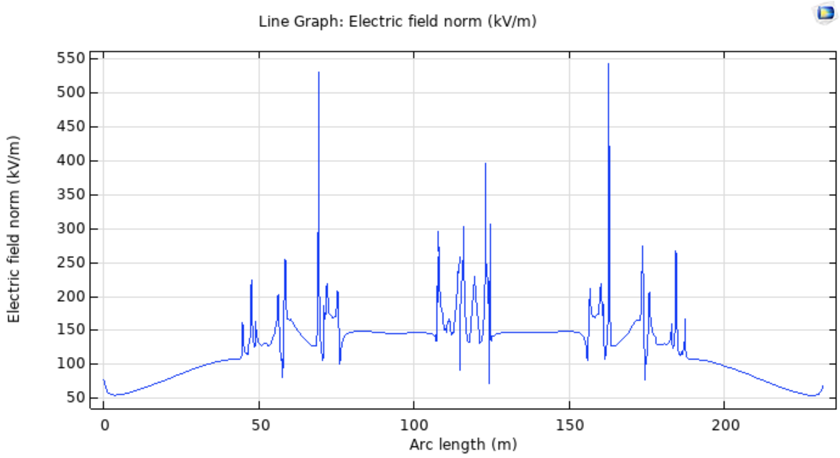


Figure 5. 22 Electric field distribution along cross-section Ruwanweliseya-30kA- Directly above at 91.2m from ground

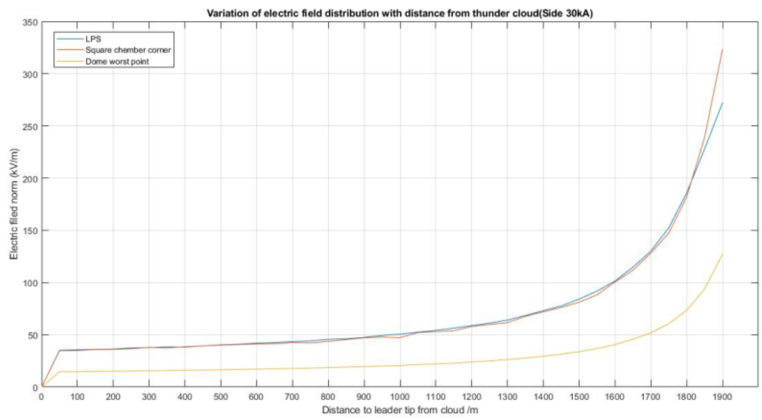


Figure 5. 23 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 22, at the corner of the square chamber, an upward leader will initiate before the LPS. Hence the corners of the square chamber are unprotected. But the dome worst point is protected by LPS. The corners of the square chamber can be damaged due to lightning. Hence a flat copper strip can be installed along the border of the square chamber to provide the required protection.

5.6.1.2 Considering 200kA surge

- **When the surge is directly above the stupa**

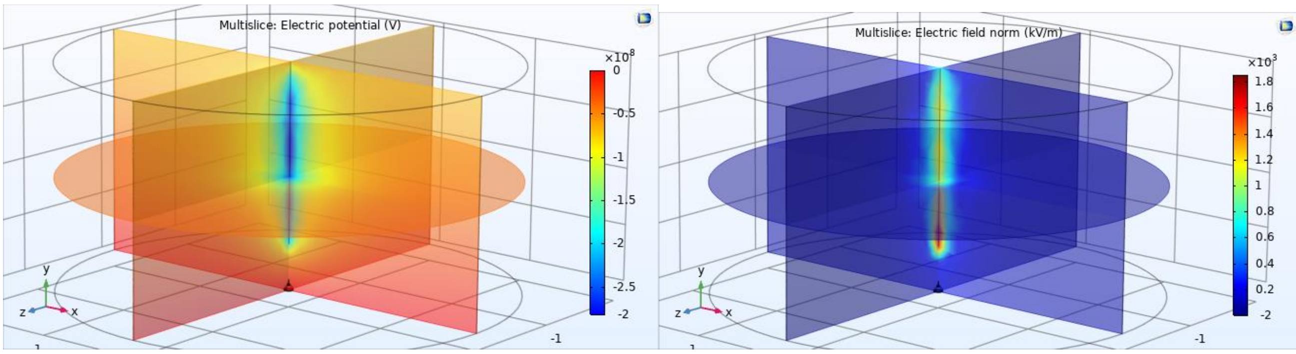


Figure 5. 24 (a)Voltage distribution for Ruwanweliseya-200kA- Directly above at 313m from tip (b) Electric field distribution for Ruwanweliseya-200kA- Directly above at 313m from tip

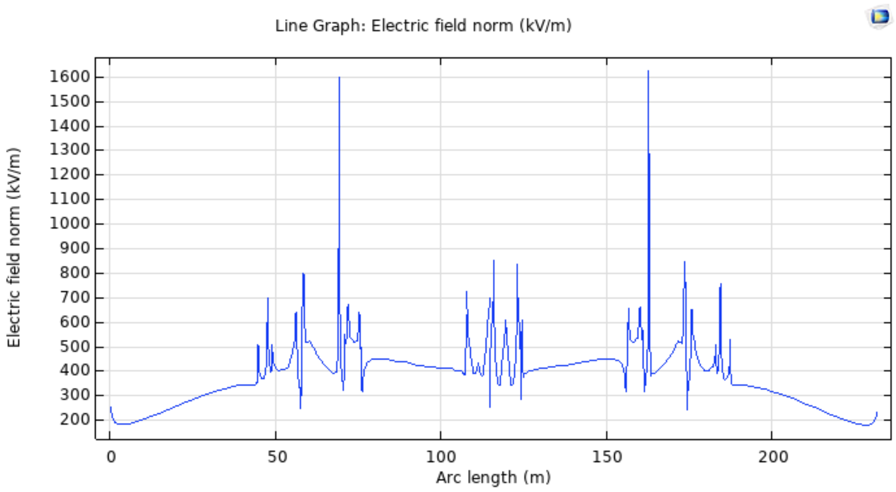


Figure 5. 25 Electric field distribution along cross-section Ruwanweliseya-200kA- Directly above at 313m from tip

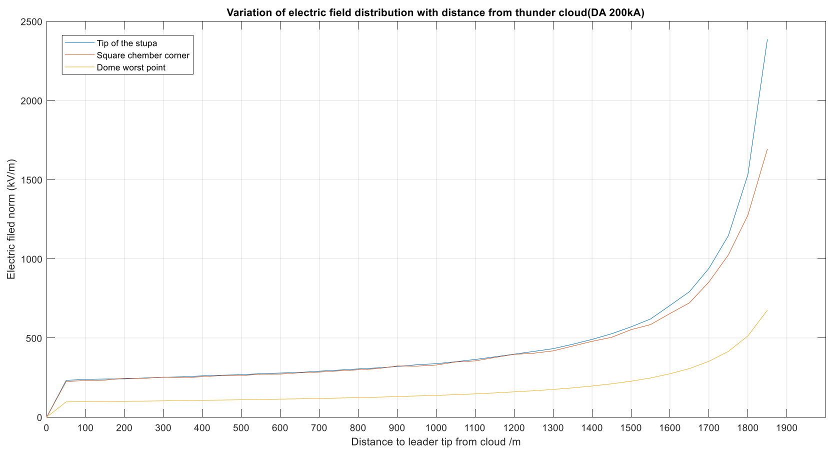


Figure 5. 26 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 25, there is a similar probability of upward leader initiation at the corners of the square chamber and at the LPS. Hence the corners of the square chamber are unprotected. But the dome worst point is protected by LPS. The corners of the square chamber can be damaged due to lightning. Hence a flat copper strip can be installed along the border of the square chamber to provide the required protection.

- **When the surge is on the side of the stupa**

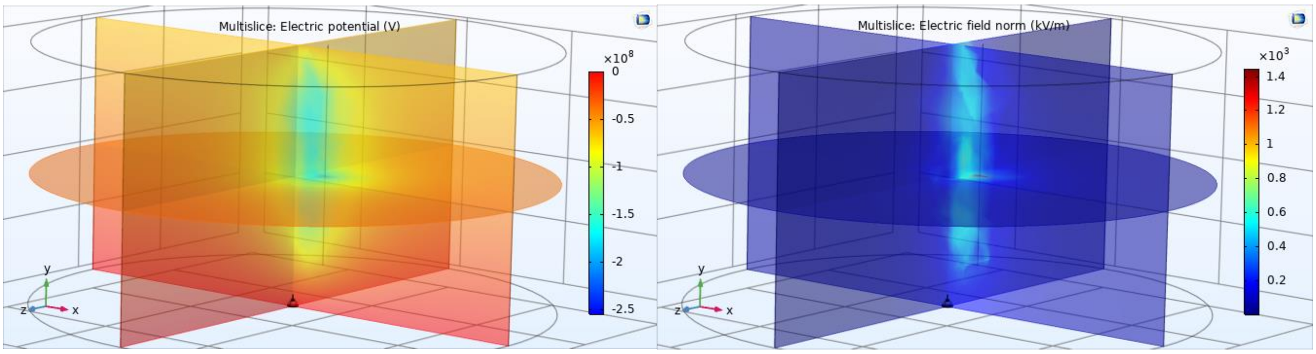


Figure 5. 27 (a) Voltage distribution for Ruwanweliseya-200kA- Directly above at 313m from tip (b) Electric field distribution for Ruwanweliseya-200kA- Directly above at 313m from tip

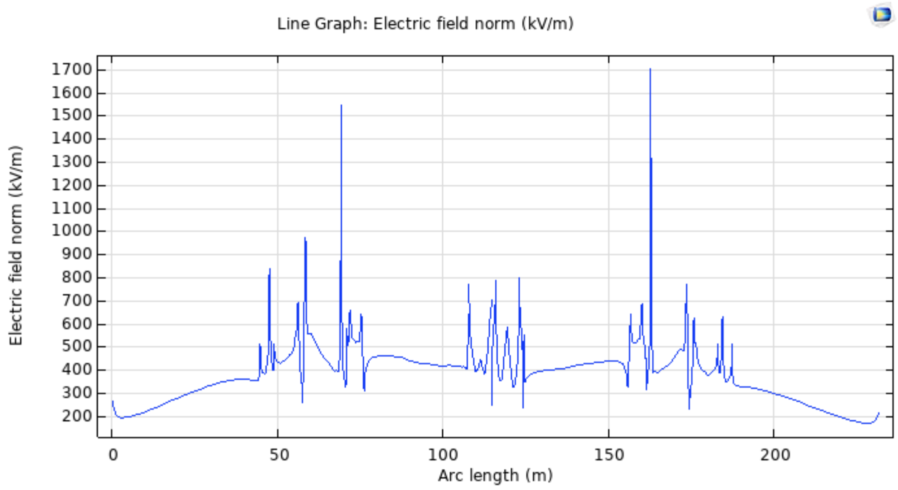


Figure 5. 28 Electric field distribution along cross-section Ruwanweliseya-200kA- Directly above at 313m from tip

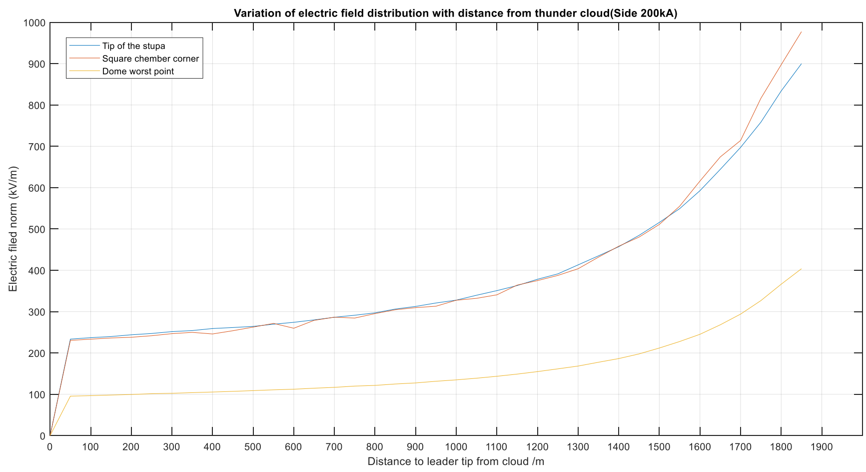


Figure 5. 29 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 28, there is an equal probability of upward leader initiation at the corner of the square chamber and at the LPS. Hence the corners of the square chamber are unprotected. But the dome worst point is protected by LPS. The corners of the square chamber can be damaged due to lightning. Hence a flat copper strip can be installed along the border of the square chamber to provide the required protection.

5.6.2 Jethawanaramaya at present dimensions

5.6.1.1 Considering 30kA surge

- **When the surge is directly above the stupa**

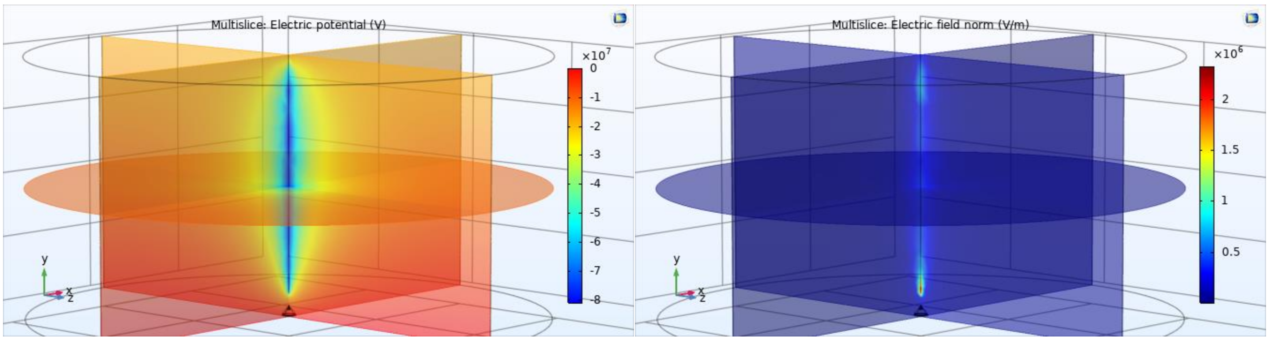


Figure 5. 30 (a) Voltage distribution for Jethawanaramaya-30kA- Directly above at 91.2m from tip (b) Electric field distribution for Jethawanaramaya -30kA- Directly above at 91.2m from tip

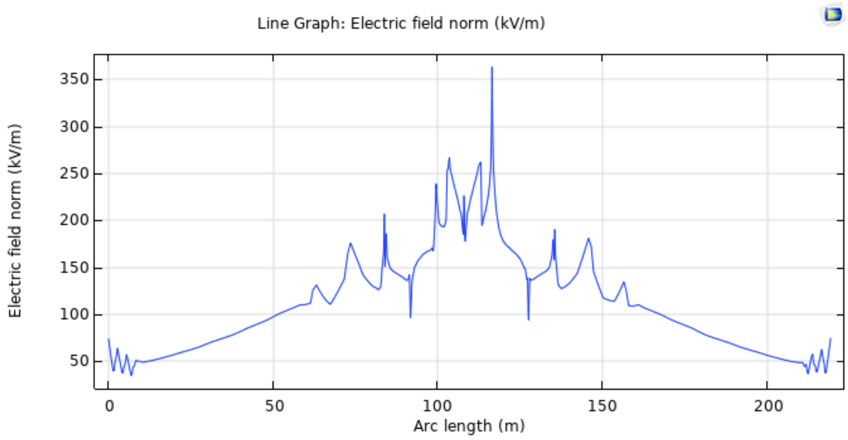


Figure 5. 31 Electric field distribution along cross-section Jethawanaramaya -30kA- Directly above at 91.2m from tip

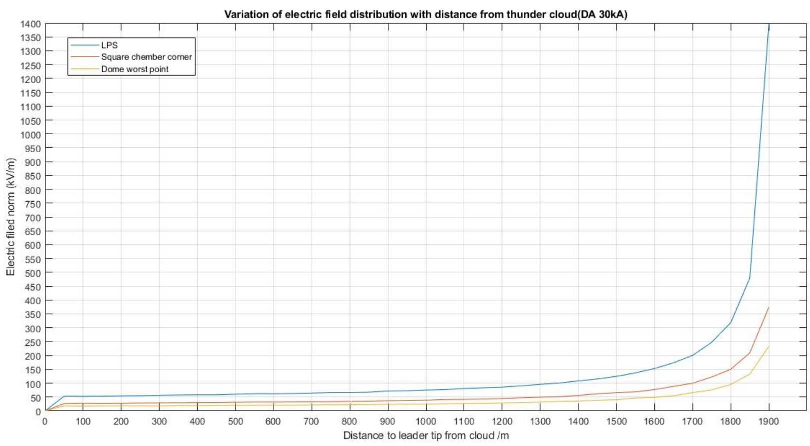


Figure 5. 32 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 31, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, as shown in figure 5.7, an upward leader will not initiate from those points. So, it can be concluded that LPS protects stupa.

- **When the surge is on the side of the stupa**

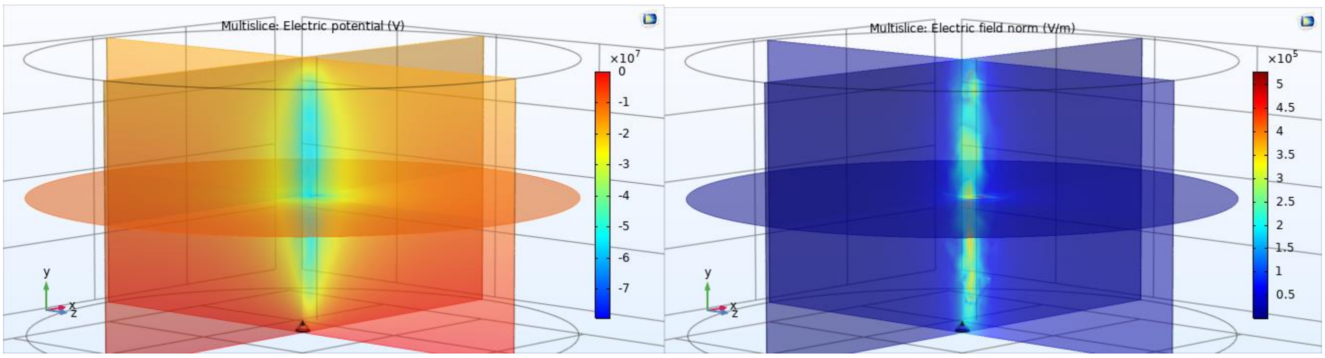


Figure 5. 33 (a) Voltage distribution for Jethawanaramaya -30kA- Directly above at 91.2m from ground
(b) Electric field distribution for Jethawanaramaya -30kA- Directly above at 91.2m from ground

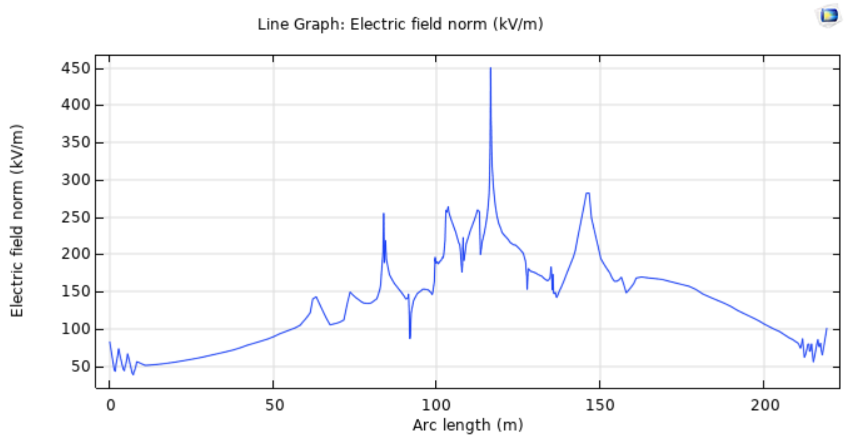


Figure 5. 34 Electric field distribution along cross-section Jethawanaramaya -30kA- Directly above at 91.2m from ground

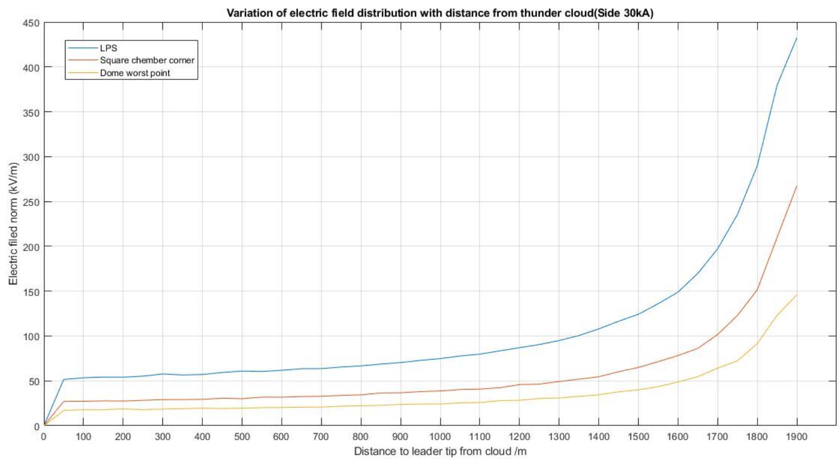


Figure 5. 35 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 34, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, as shown in figure 5.7, an upward leader will not initiate from those points. So, it can be concluded that LPS protects stupa.

5.6.1.2 Considering 200kA surge

- **When the surge is directly above the stupa**

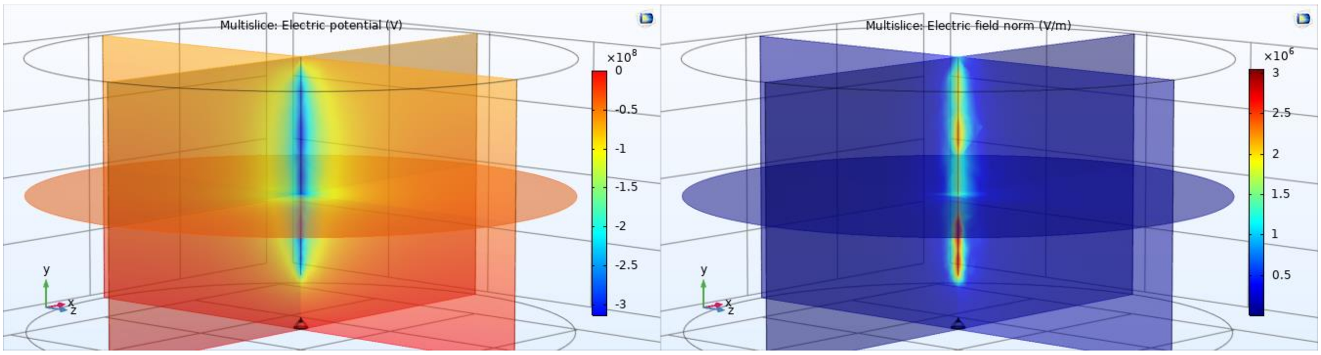


Figure 5. 36 (a) Voltage distribution for Jethawanaramaya -200kA- Directly above at 313m from tip (b) Electric field distribution for Jethawanaramaya -200kA- Directly above at 313m from tip

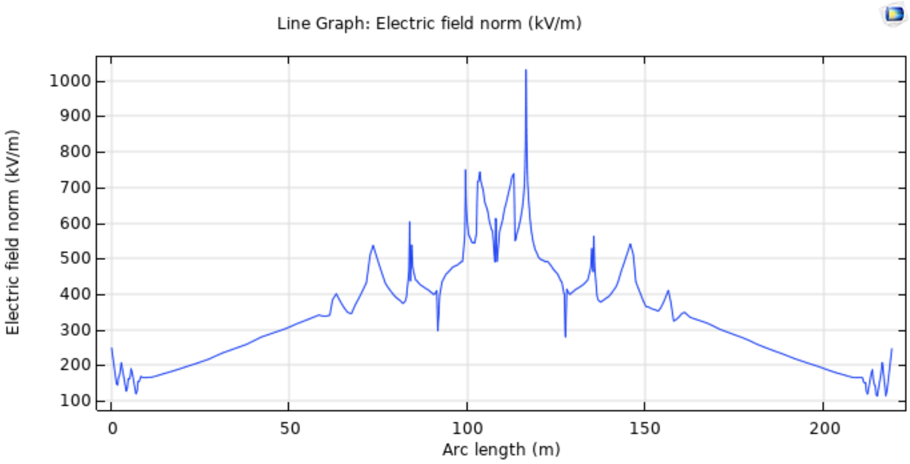


Figure 5. 37 Electric field distribution along cross-section Jethawanaramaya -200kA- Directly above at 313m from tip

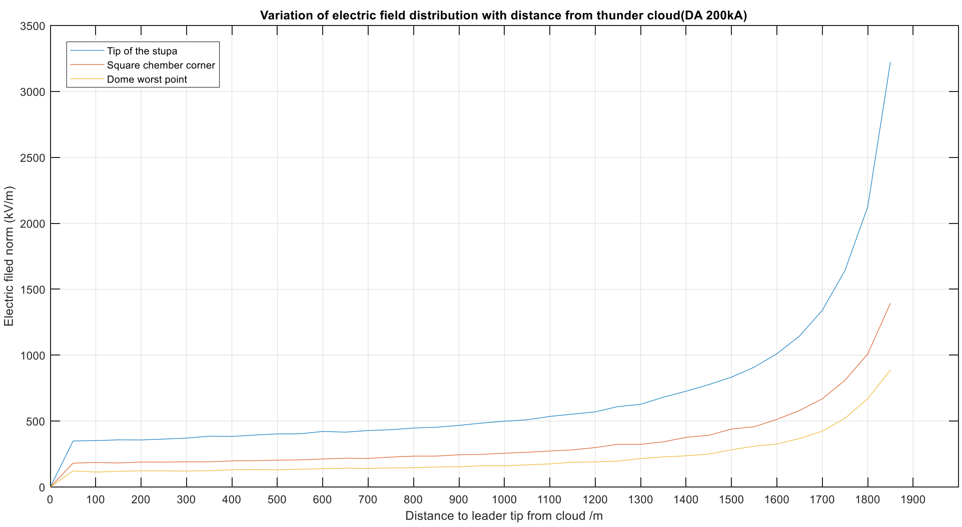


Figure 5. 38 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 37, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, as shown in figure 5.7, an upward leader will not initiate from those points. So, it can be concluded that LPS protects stupa.

- **When the surge is on the side of the stupa**

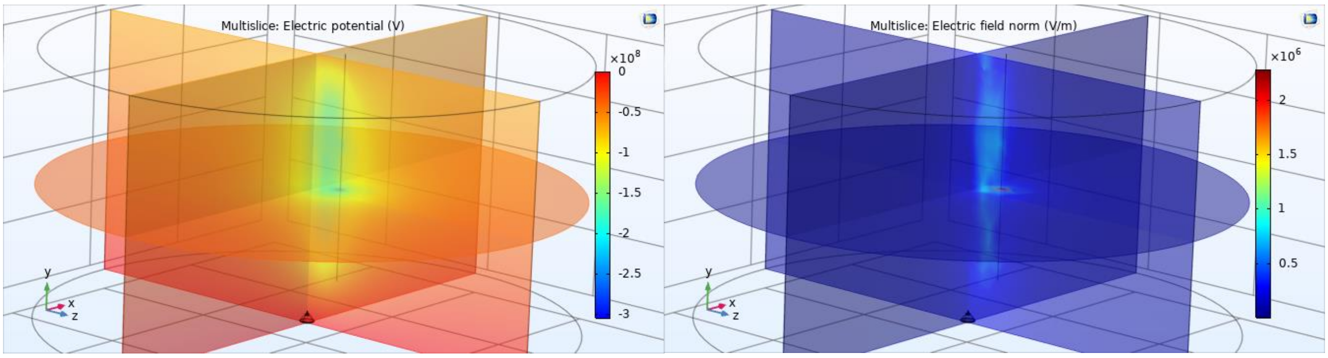


Figure 5. 39 (a) Voltage distribution for Jethawanaramaya -200kA- Directly above at 313m from tip (b) Electric field distribution for Jethawanaramaya -200kA- Directly above at 313m from tip

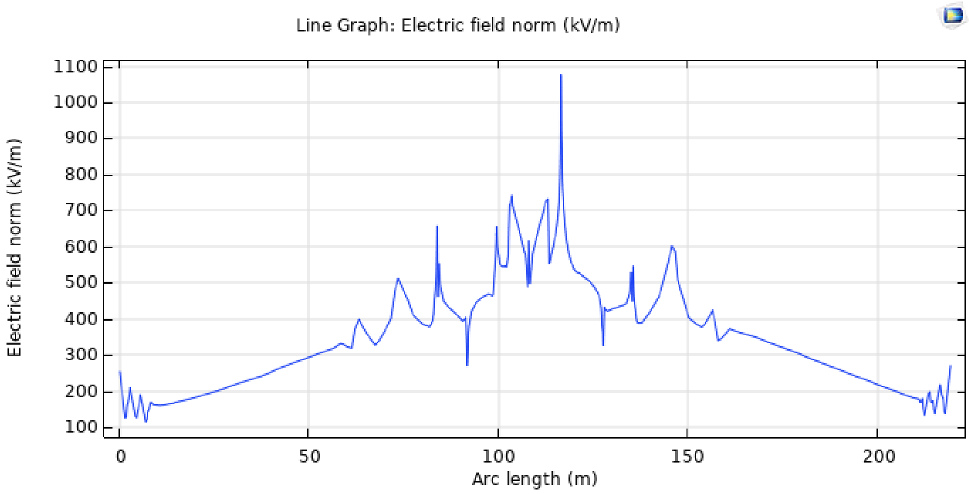


Figure 5. 40 Electric field distribution along cross-section Jethawanaramaya -200kA- Directly above at 313m from tip

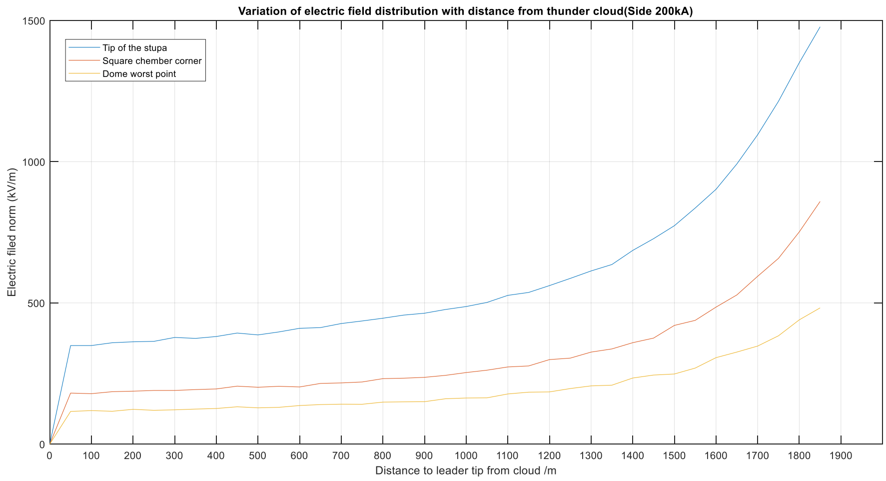


Figure 5. 41 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 41, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Even if there is a possibility that an upward leader will initiate from the square chamber according to figure 5. 40, it will be protected since the electric field at LPS is significantly higher. Also, for the dome worst point, which is the unprotected region obtained from RSM, as shown in figure 5.7, an upward leader will not initiate. So, it can be concluded that LPS will protect the stupa.

5.6.3 Abayagiriya at present dimensions

5.6.1.1 Considering 30kA surge

- **When the surge is directly above the stupa**

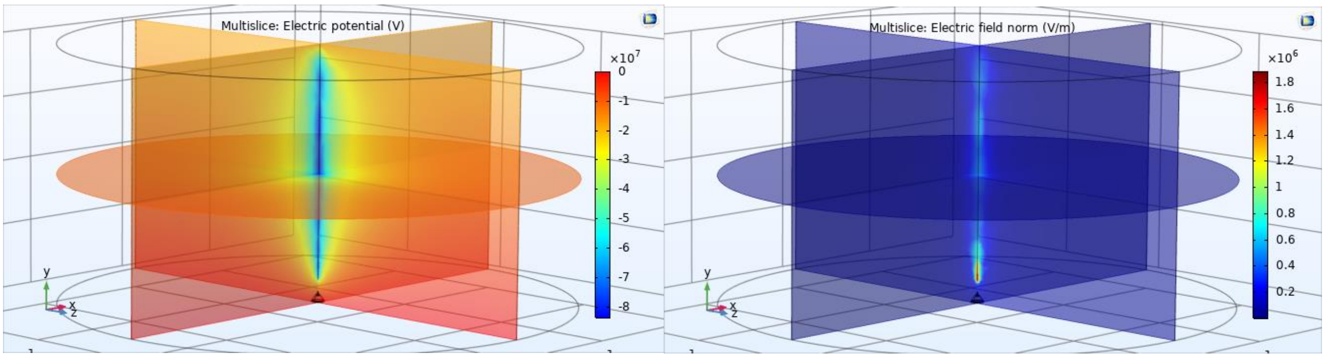


Figure 5. 42 (a) Voltage distribution for Abayagiriya-30kA- Directly above at 91.2m from tip (b) Electric field distribution for Abayagiriya -30kA- Directly above at 91.2m from tip

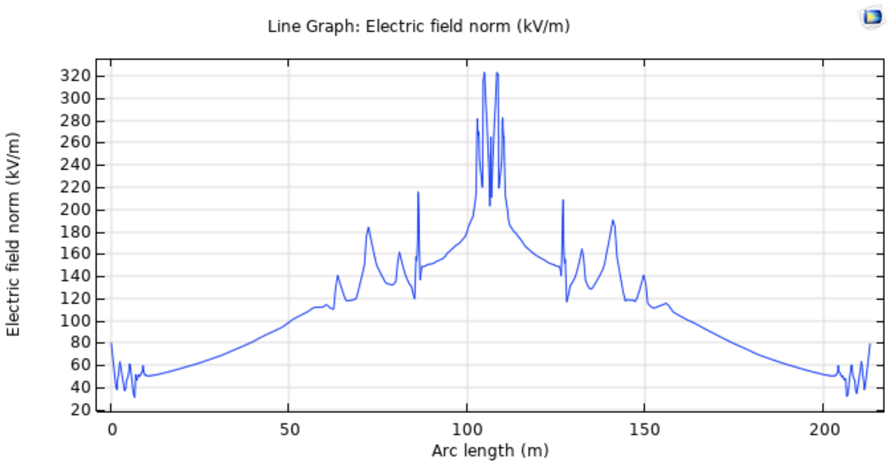


Figure 5. 43 Electric field distribution along cross-section Abayagiriya -30kA- Directly above at 91.2m from tip

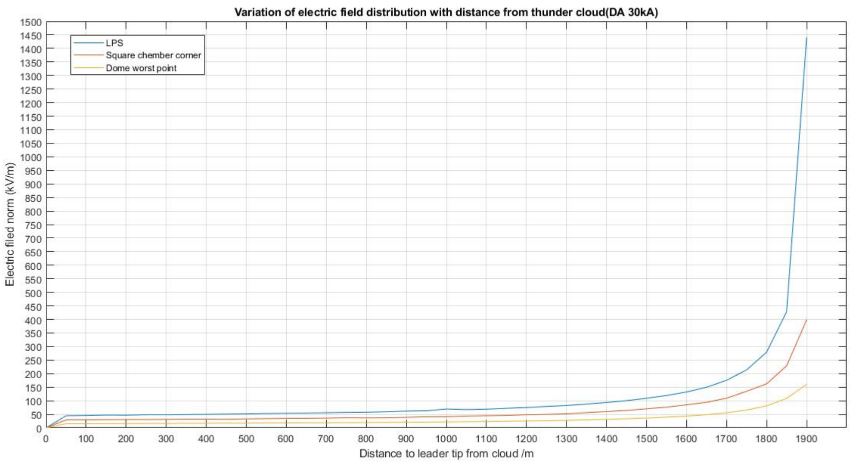


Figure 5. 44 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 43, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, as shown in figure 5.6, an upward leader will not initiate from those points. So, it can be concluded that LPS protects stupa.

- **When the surge is on the side of the stupa**

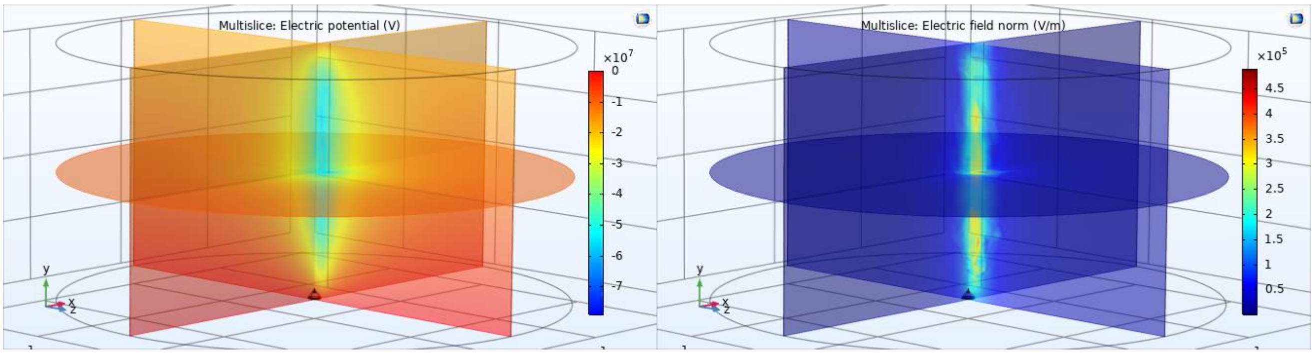


Figure 5. 45 (a) Voltage distribution for Abayagiriya a-30kA- Directly above at 91.2m from ground (b) Electric field distribution for Abayagiriya -30kA- Directly above at 91.2m from ground

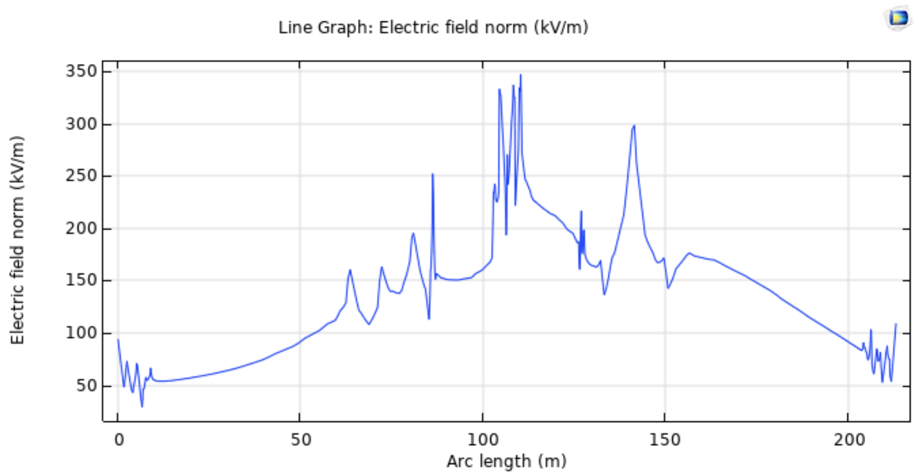


Figure 5. 46 Electric field distribution along cross-section Abayagiriya -30kA- Directly above at 91.2m from ground

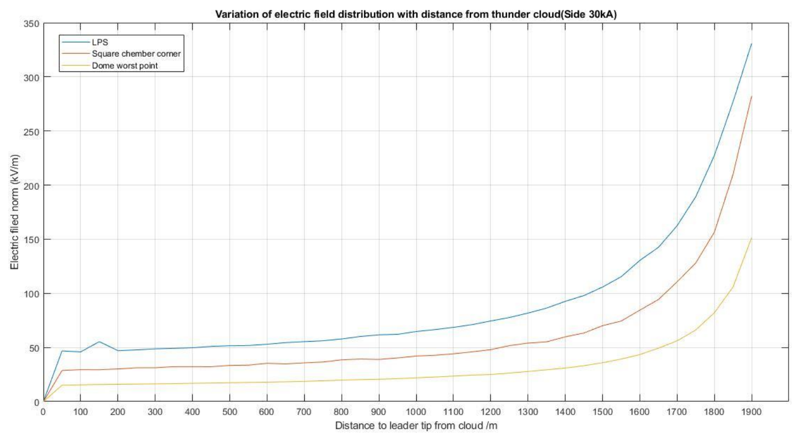


Figure 5. 47 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 46, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. But according to figure 5. 47, there is a possibility that an upward leader will initiate from the square chamber corner close to downward leader as well. Also, for the dome worst point, which is the unprotected region obtained from RSM, as shown in figure 5.8, an upward leader will not initiate. So, it can be concluded that LPS does not protect stupa. Hence a flat copper strip can be installed along the border of the square chamber to provide the required protection.

5.6.1.2 Considering 200kA surge

- **When the surge is directly above the stupa**

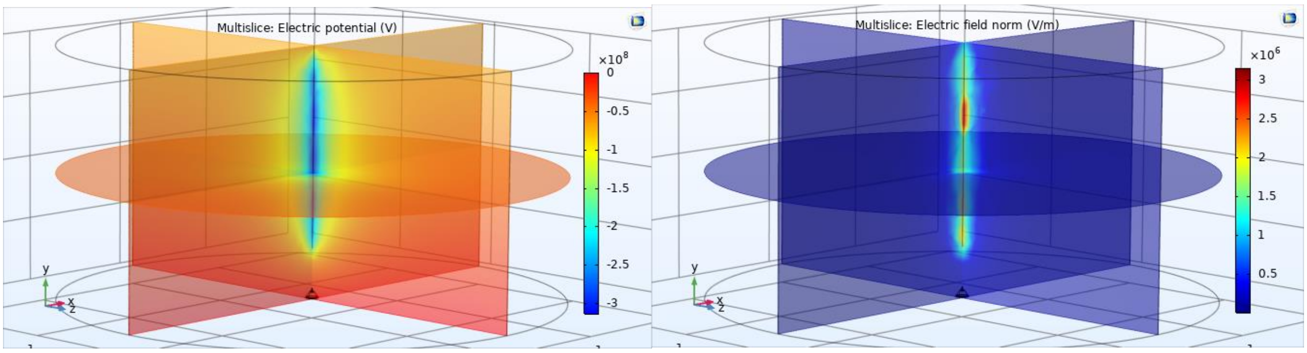


Figure 5. 48 (a)Voltage distribution for Abayagiriya -200kA- Directly above at 313m from tip (b) Electric field distribution for Abayagiriya -200kA- Directly above at 313m from tip

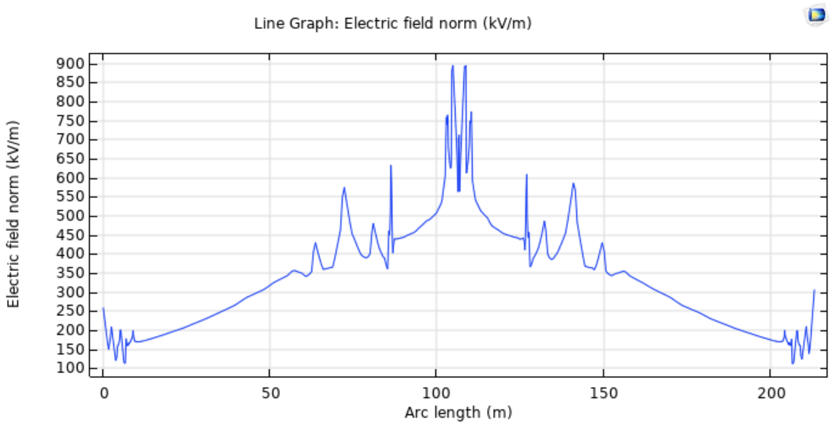


Figure 5. 49 Electric field distribution along cross-section Abayagiriya 200kA- Directly above at 313m from tip

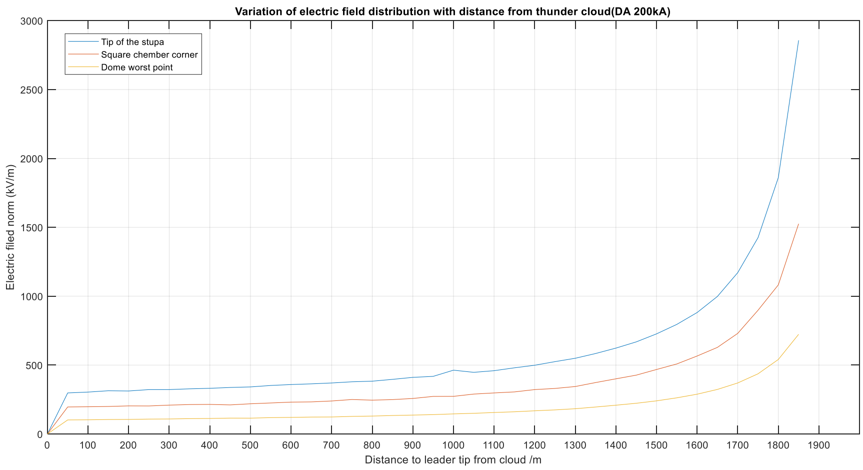


Figure 5. 50 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 49, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Even if there is a possibility that an upward leader will initiate from the square chamber according to figure 5. 50, it will be protected since the electric field at LPS is significantly higher. Also, for the dome worst point, which is the unprotected region obtained from RSM, as shown in figure 5.6, an upward leader will not initiate. So, it can be concluded that LPS will protect the stupa.

- **When the surge is on the side of the stupa**

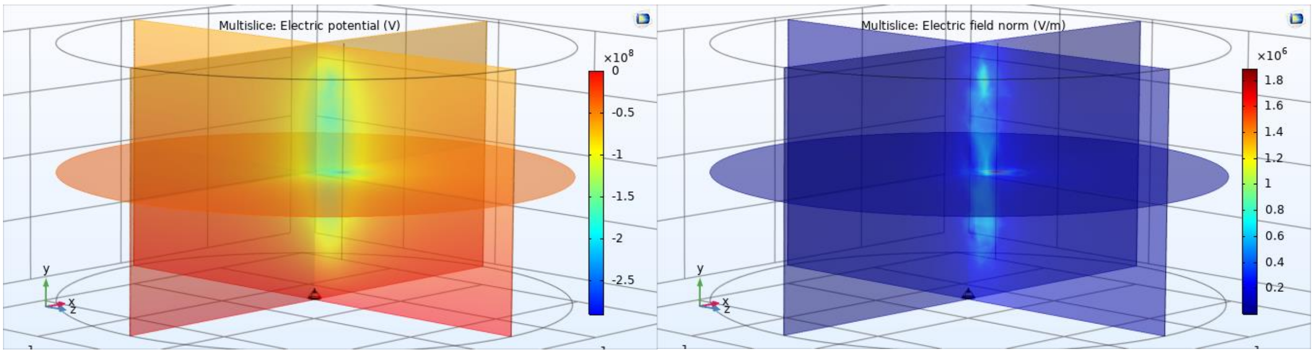


Figure 5. 51 (a) Voltage distribution for Abayagiriya -200kA- Directly above at 313m from tip (b) Electric field distribution for Abayagiriya -200kA- Directly above at 313m from tip

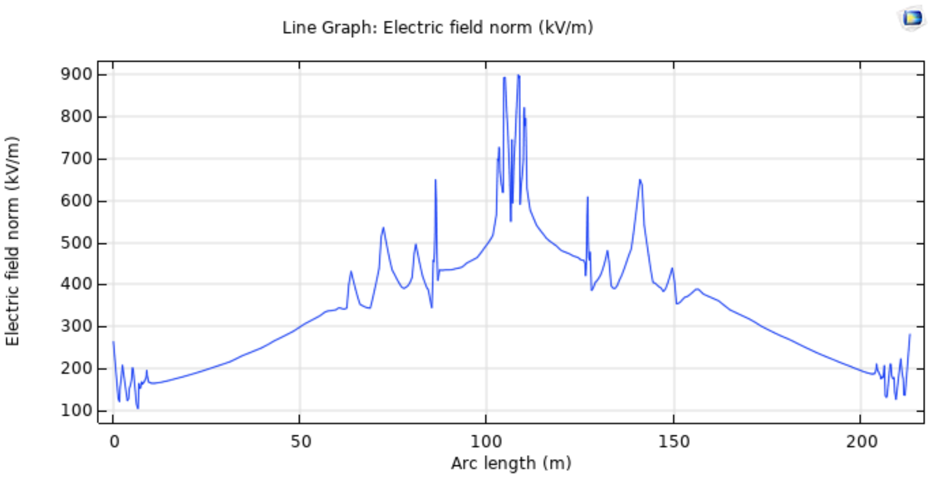


Figure 5. 52 Electric field distribution along cross-section Abayagiriya 200kA- Directly above at 313m from tip

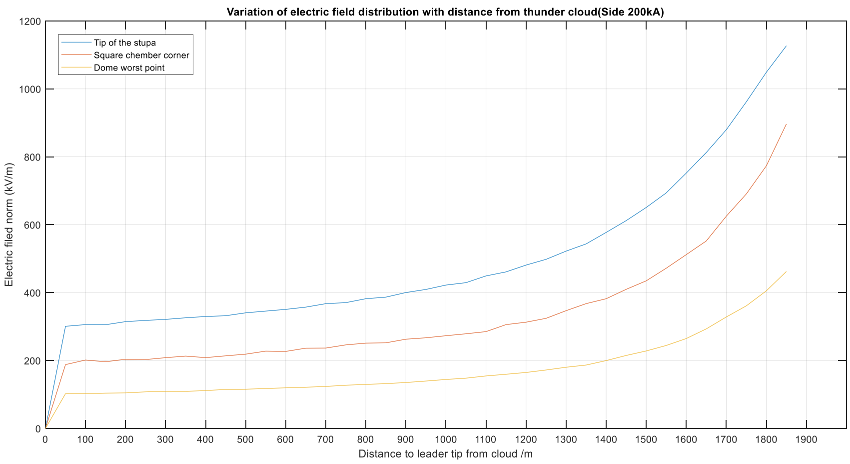


Figure 5. 53 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 53, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Even if there is a possibility that an upward leader will initiate from the square chamber according to figure 5. 52, it will be protected since the electric field at LPS is significantly higher. Also, for the dome worst point, which is the unprotected region obtained from RSM, as shown in figure 5.8, an upward leader will not initiate. So, it can be concluded that LPS will protect the stupa.

5.6.4 Mirisawatiya at present dimensions

5.6.1.1 Considering 30kA surge

- **When the surge is directly above the stupa**

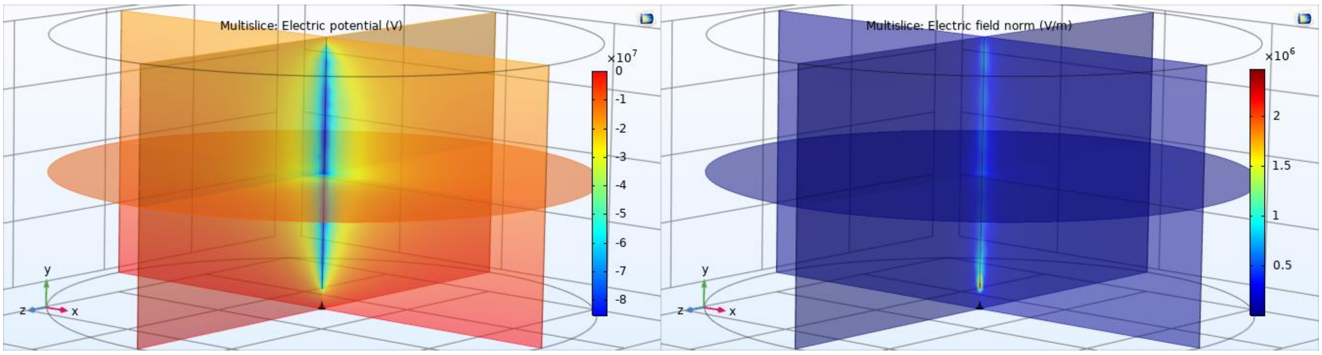


Figure 5. 54 (a) Voltage distribution for Mirisawetiya-30kA- Directly above at 91.2m from tip (b) Electric field distribution for Mirisawetiya -30kA- Directly above at 91.2m from tip

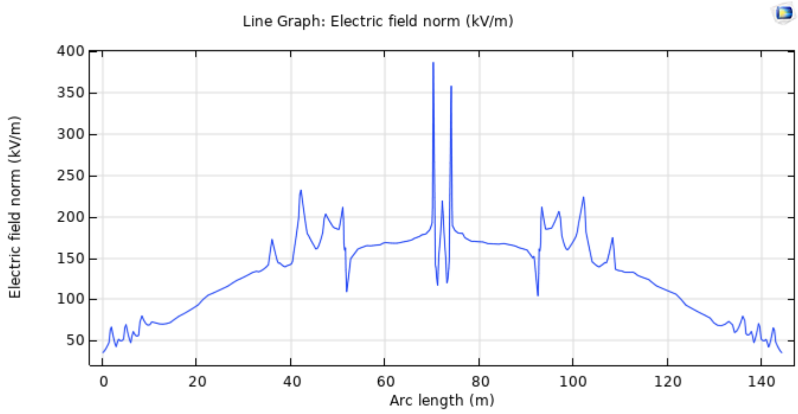


Figure 5. 55 Electric field distribution along cross-section Mirisawetiya -30kA- Directly above at 91.2m from tip

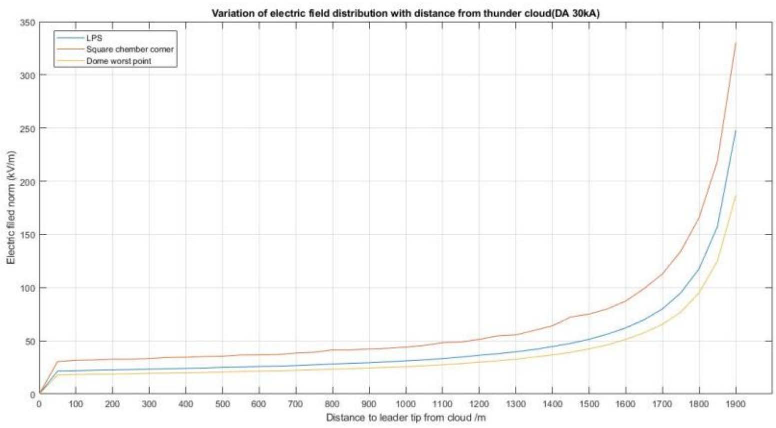


Figure 5. 56 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 55, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, as shown in figure 5.8, an upward leader will not initiate from those points. So, it can be concluded that LPS protects stupa.

- **When the surge is on the side of the stupa**

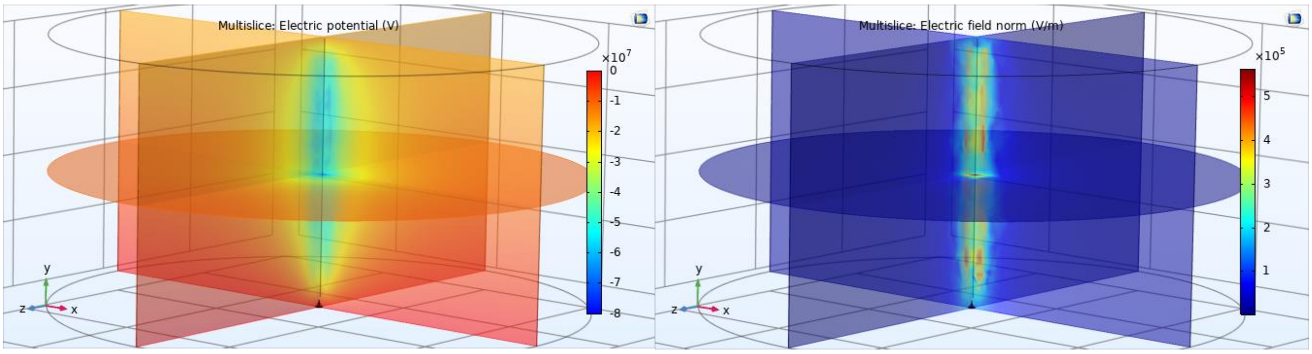


Figure 5. 57 (a) Voltage distribution for Mirisawetiya -30kA- Directly above at 91.2m from ground (b) Electric field distribution for Mirisawetiya -30kA- Directly above at 91.2m from ground

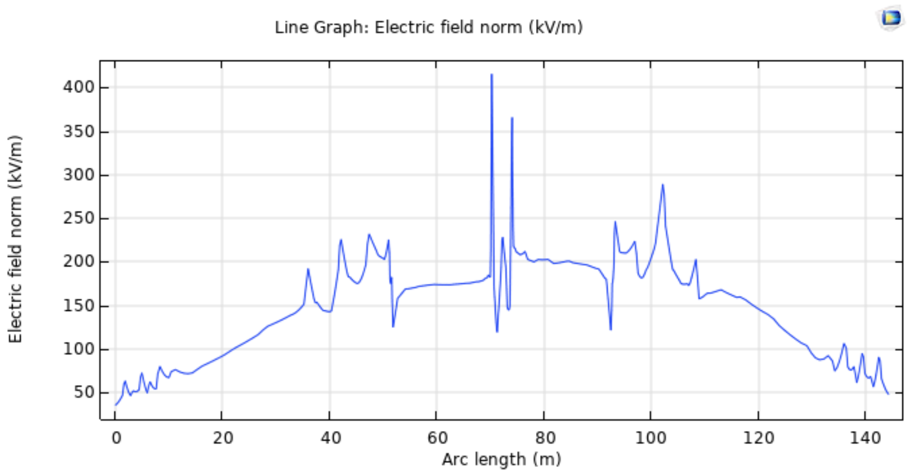


Figure 5. 58 Electric field distribution along cross-section Mirisawetiya-30kA- Directly above at 91.2m from ground

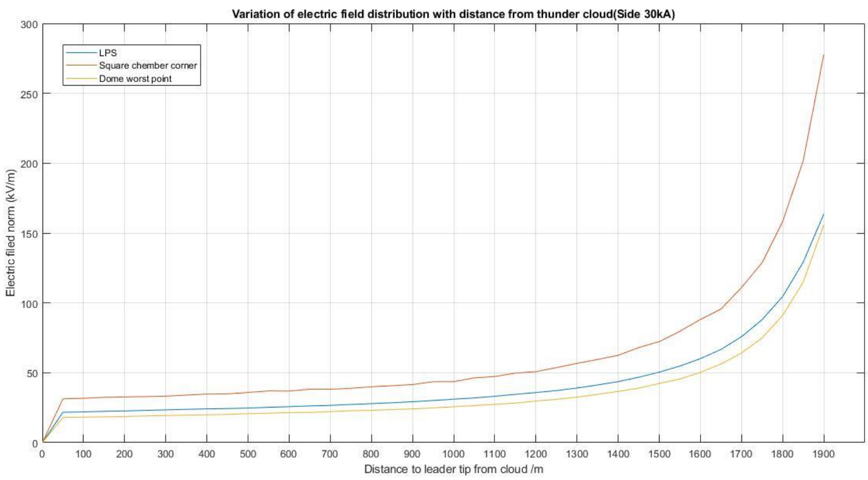


Figure 5. 59 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 58, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, as shown in figure 5.8, an upward leader will not initiate from those points. So, it can be concluded that LPS protects stupa.

5.6.1.2 Considering 200kA surge

- **When the surge is directly above the stupa**

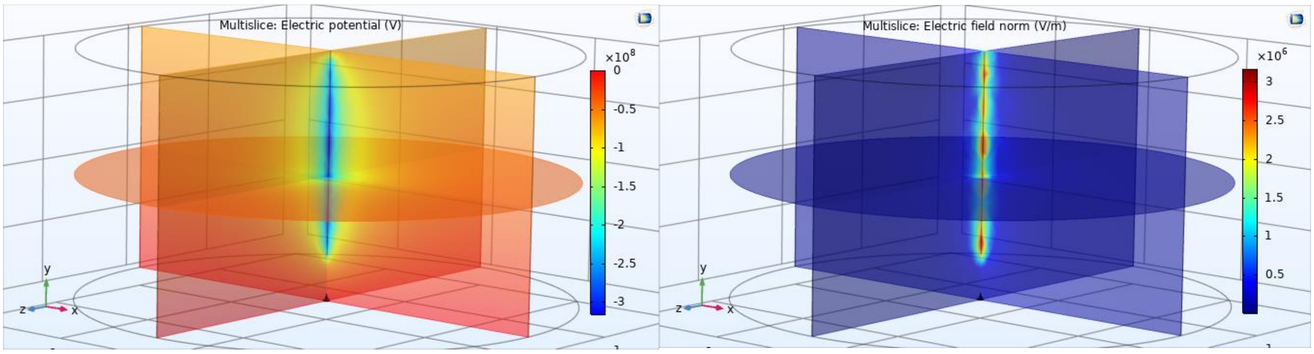


Figure 5. 60 (a) Voltage distribution for Mirisawetiya -200kA- Directly above at 313m from tip (b) Electric field distribution for Mirisawetiya 200kA- Directly above at 313m from tip

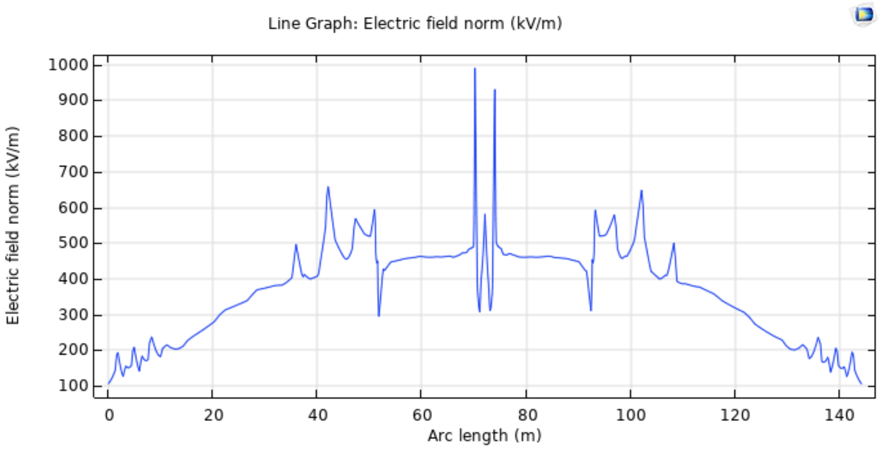


Figure 5. 61 Electric field distribution along cross-section Mirisawetiya -200kA- Directly above at 313m from tip

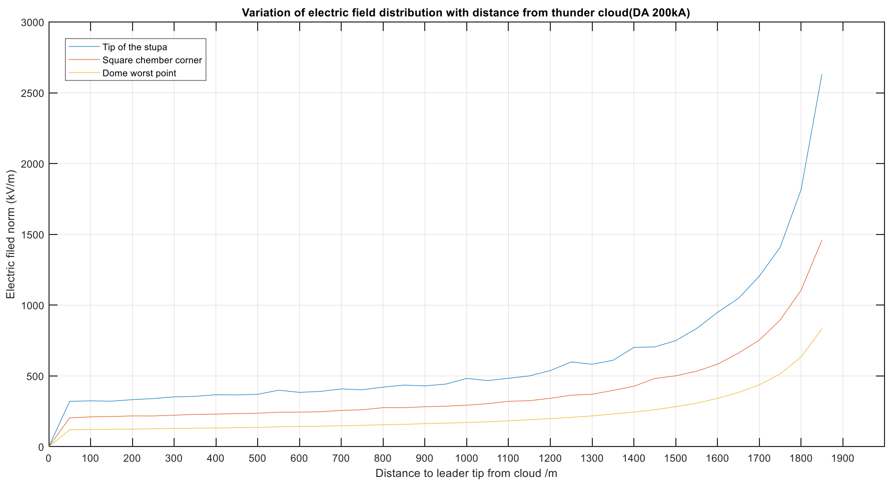


Figure 5. 62 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 62, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Even if there is a possibility that an upward leader will initiate from the square chamber according to figure 5. 61, it will be protected since the electric field at LPS is significantly higher. Also, for the dome worst point, which is the unprotected region obtained from RSM, as shown in figure 5.8, an upward leader will not initiate. So, it can be concluded that LPS will protect the stupa.

- **When the surge is on the side of the stupa**

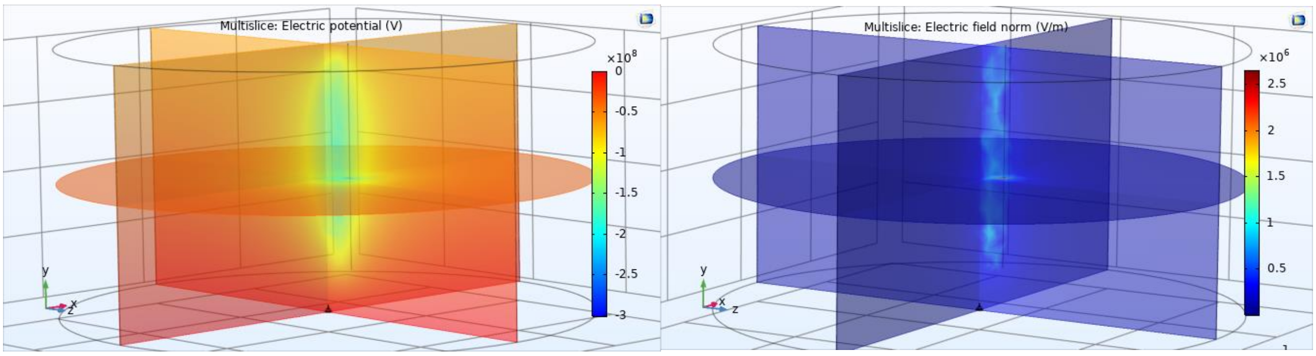


Figure 5. 63 (a) Voltage distribution for Mirisawetiya -200kA- Directly above at 313m from tip (b) Electric field distribution for Mirisawetiya -200kA- Directly above at 313m from tip

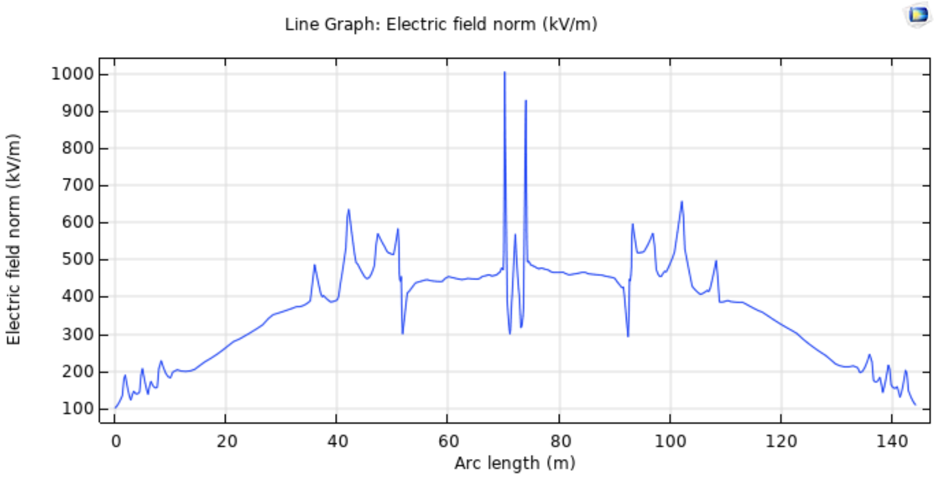


Figure 5. 64 Electric field distribution along cross-section Mirisawetiya -200kA- Directly above at 313m from tip

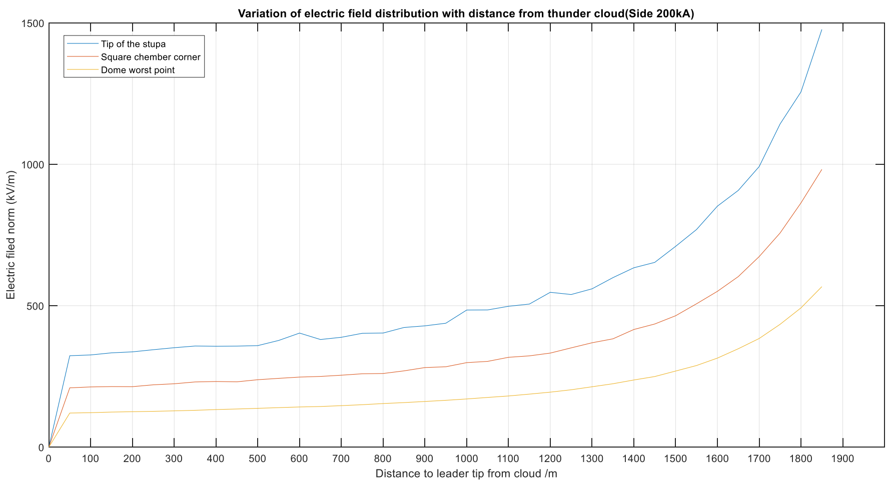


Figure 5. 65 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 65, at the lightning protection system(LPS) situated at the tip of the stupa, an upward leader will initiate. Even if there is a possibility that an upward leader will initiate from the square chamber according to figure 5. 64., it will be protected since the electric field at LPS is significantly higher. Also, for the dome worst point, which is the unprotected region obtained from RSM, as shown in figure 5.8, an upward leader will not initiate. So, it can be concluded that LPS will protect the stupa.

5.6.1 Ruwanweliseya at ancient dimensions

5.6.1.1 Considering 30kA surge

- **When the surge is directly above the stupa**

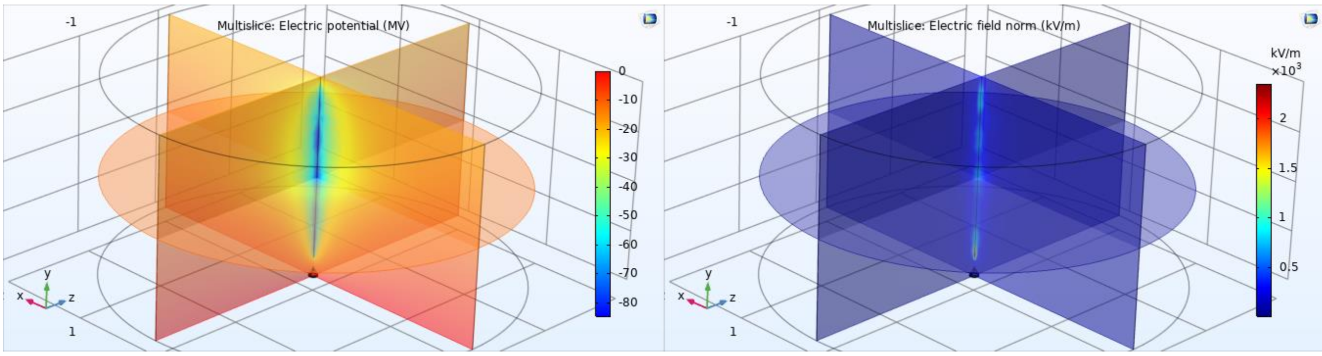


Figure 5. 66 (a) Voltage distribution for Ruwanweliseya-30kA- Directly above at 91.2m from tip
(b) Electric field distribution for Ruwanweliseya-30kA- Directly above at 91.2m from tip

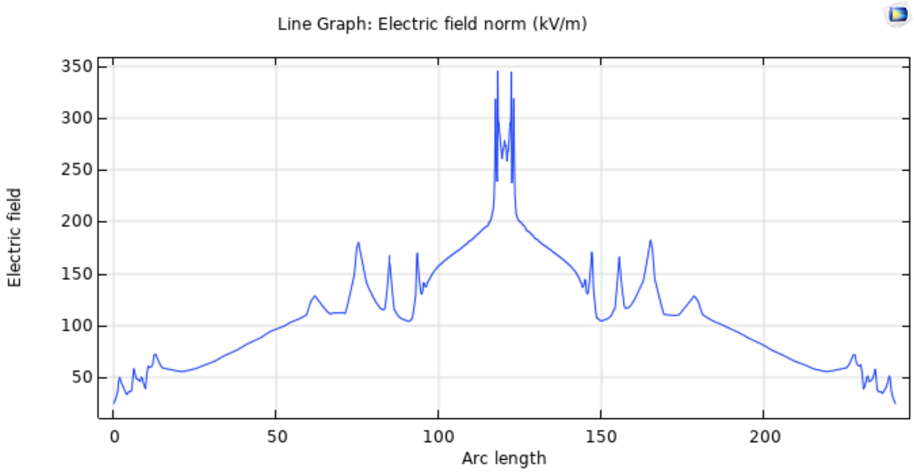


Figure 5. 67 Electric field distribution along cross-section Ruwanweliseya-30kA- Directly above at 91.2m from tip

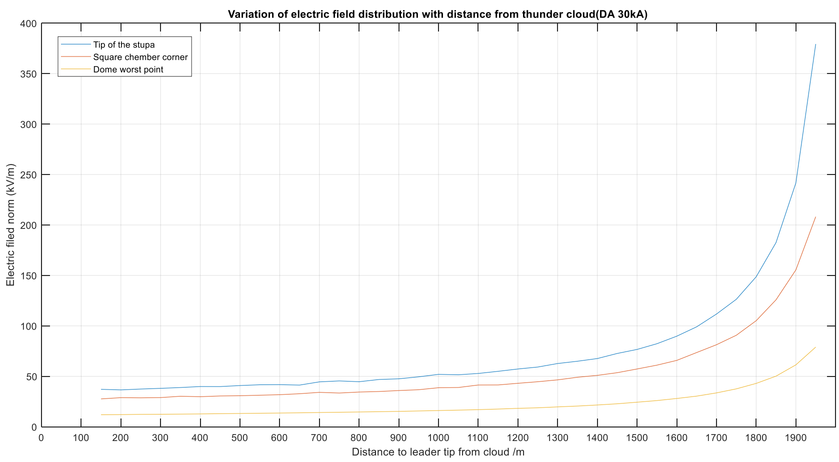


Figure 5. 68 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 67, at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, an upward leader will not initiate from those points. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

- **When the surge is on the side of the stupa**

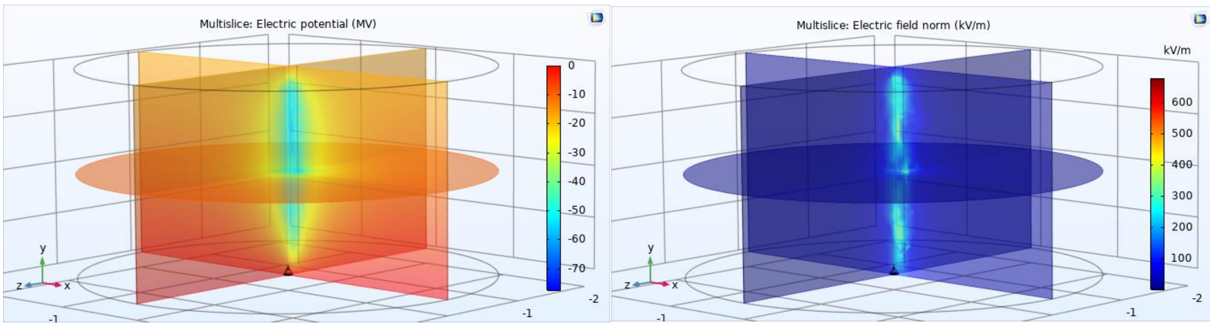


Figure 5. 69 (a) Voltage distribution for Ruwanweliseya-30kA- Directly above at 91.2m from ground (b) Electric field distribution for Ruwanweliseya-30kA- Directly above at 91.2m from ground

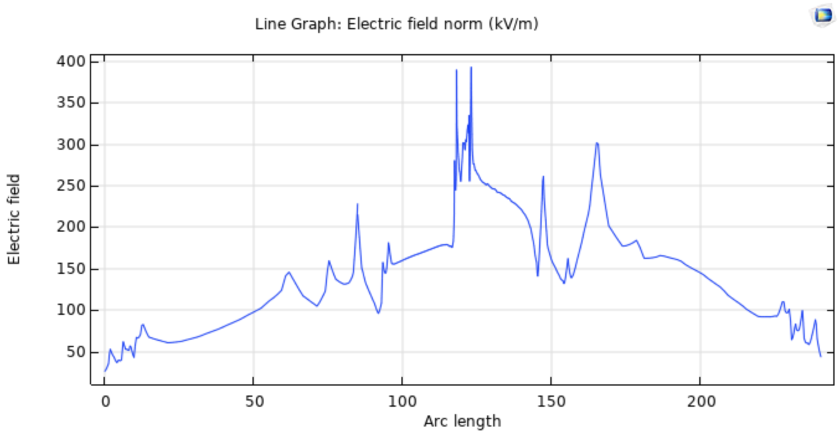


Figure 5. 70 Electric field distribution along cross-section Ruwanweliseya-30kA- Directly above at 91.2m from ground

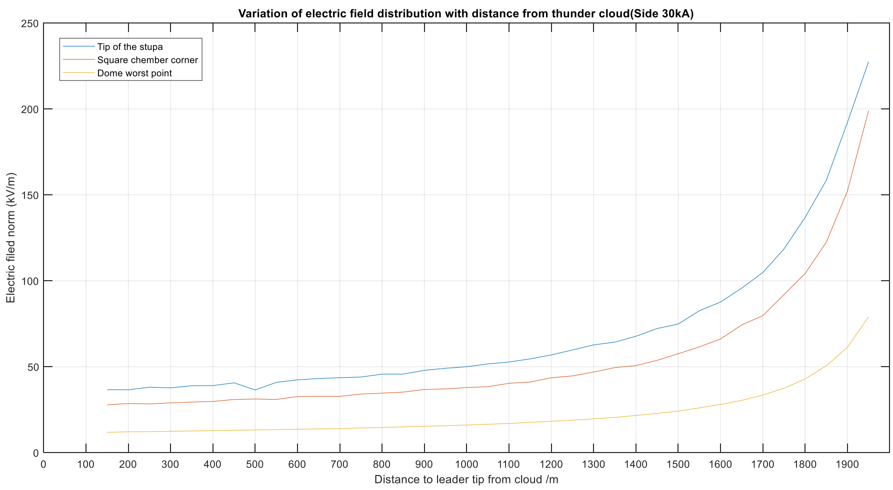


Figure 5. 71 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 71, at the tip of the stupa, an upward leader will initiate. But according to figure 5. 70, there is a possibility that an upward leader will initiate from the square chamber corner closer to downward leader as well. Also, for the dome worst point, which is the unprotected region obtained from RSM, an upward leader will not initiate. So, it can be concluded that the tip of the stupa and square chamber corners are vulnerable to a lightning strike.

5.6.1.2 Considering 200kA surge

- **When the surge is directly above the stupa**

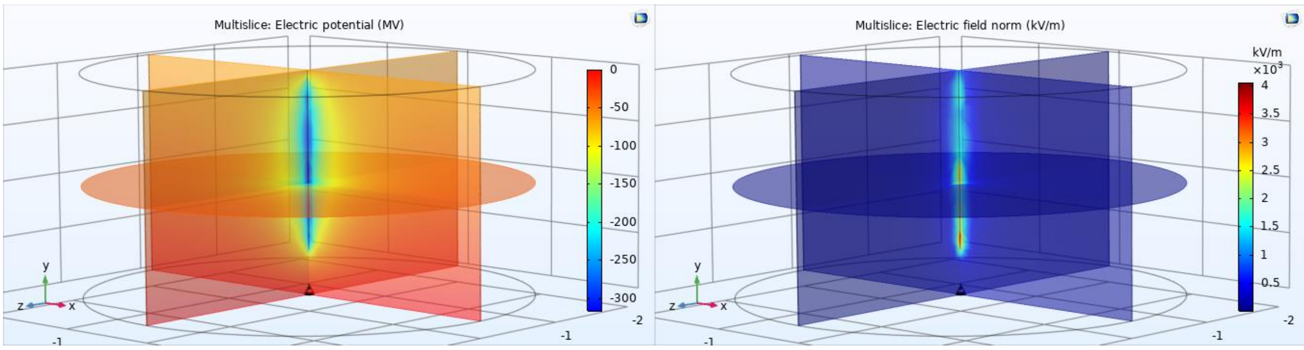


Figure 5. 72 (a) Voltage distribution for Ruwanweliseya-200kA- Directly above at 313m from tip (b) Electric field distribution for Ruwanweliseya-200kA- Directly above at 313m from tip

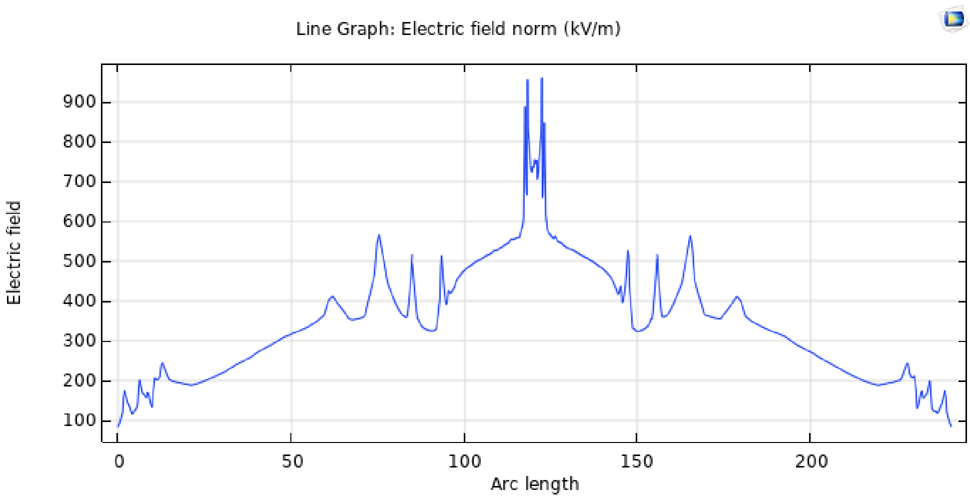


Figure 5. 73 Electric field distribution along cross-section Ruwanweliseya-200kA- Directly above at 313m from tip

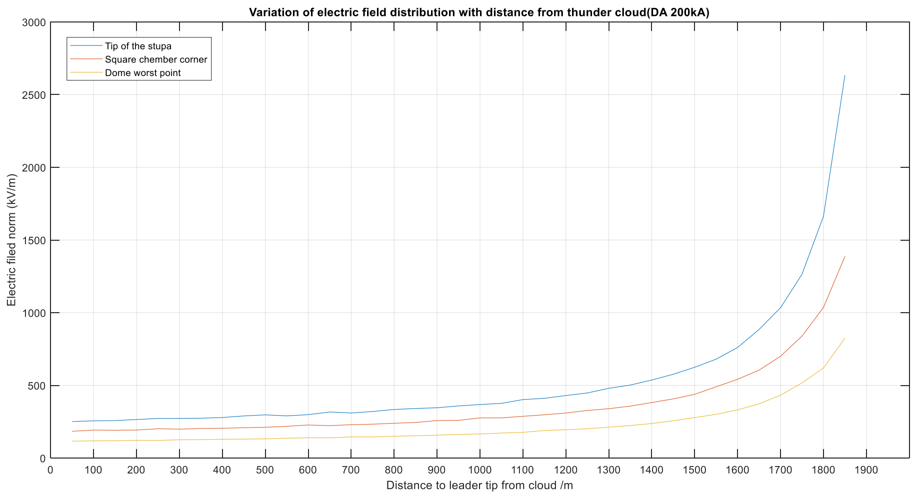


Figure 5. 74 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 74, at the tip of the stupa, an upward leader will initiate. Even if there is a possibility that an upward leader will initiate from the square chamber and dome worst points according to figure 5. 73, the downward leader will connect to the tip of the stupa since it electric field is much higher. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

- **When the surge is on the side of the stupa**

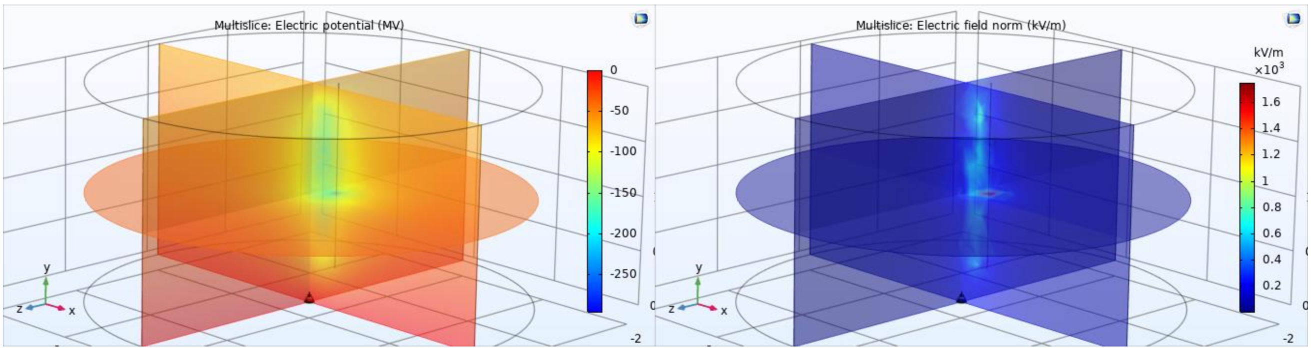


Figure 5. 75 (a) Voltage distribution for Ruwanweliseya-200kA- Directly above at 313m from tip (b) Electric field distribution for Ruwanweliseya-200kA- Directly above at 313m from tip

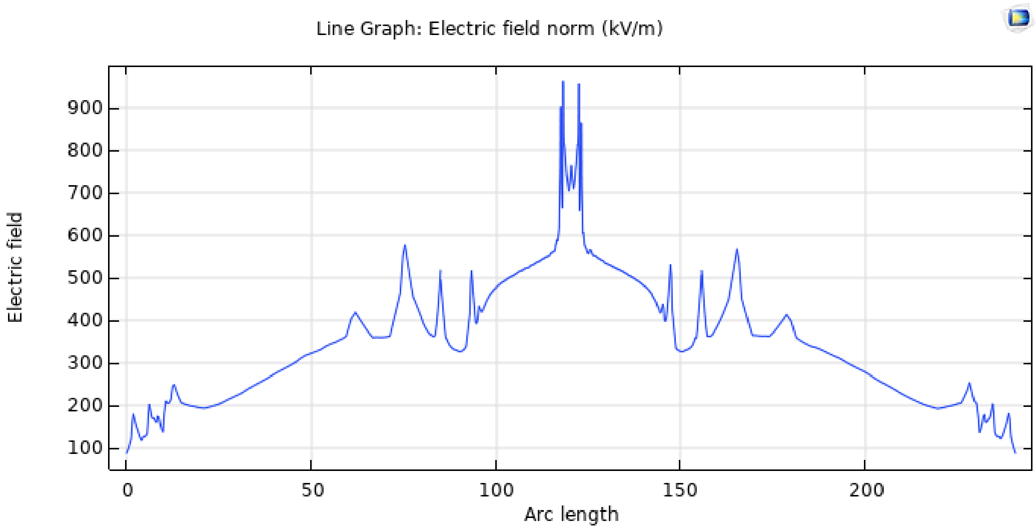


Figure 5. 76 Electric field distribution along cross-section Ruwanweliseya-200kA- Directly above at 313m from tip

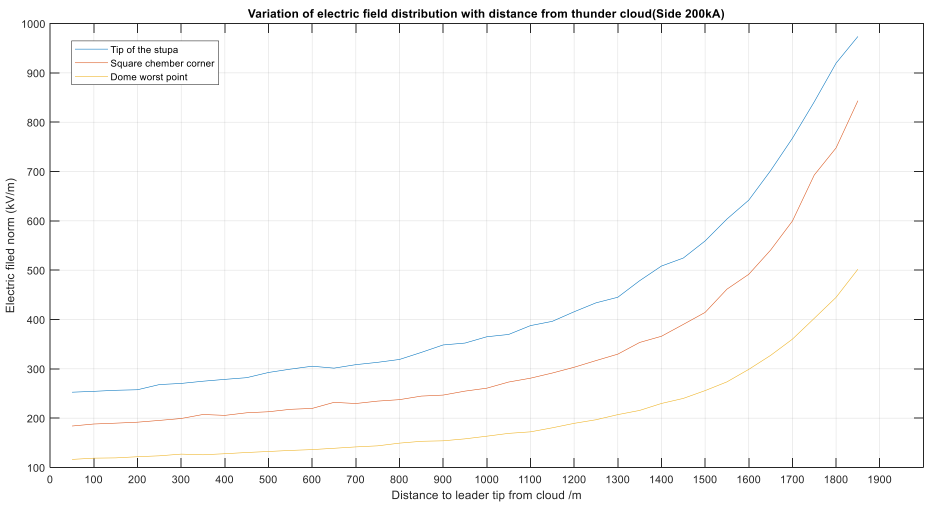


Figure 5. 77 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 77, at the tip of the stupa, an upward leader will initiate. Even if there is a possibility that an upward leader will initiate from the square chamber and dome worst points according to figure 5. 76, the downward leader will connect to the tip of the stupa since it electric field is much higher. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

5.6.2 Jethawanaramaya at ancient dimensions

5.6.1.1 Considering 30kA surge

- **When the surge is directly above the stupa**

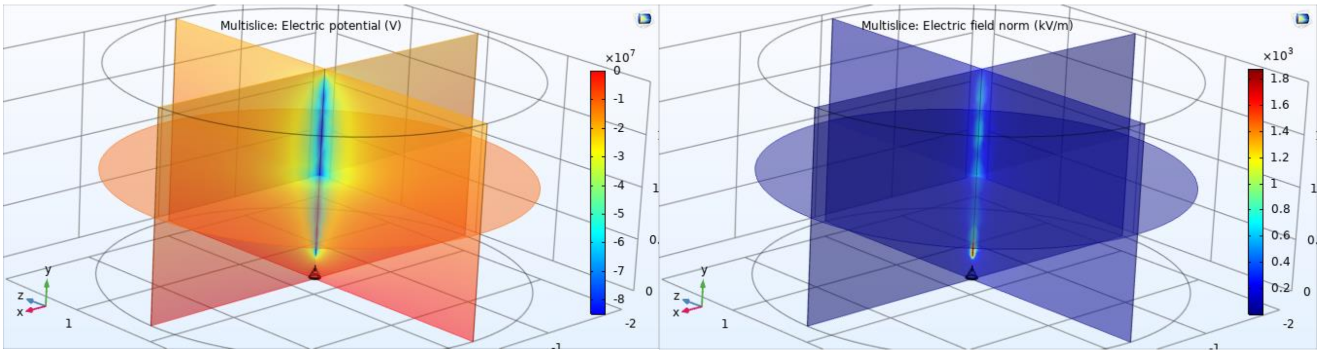


Figure 5. 78 (a) Voltage distribution for Jethawanaramaya-30kA- Directly above at 91.2m from tip (b) Electric field distribution for Jethawanaramaya -30kA- Directly above at 91.2m from tip

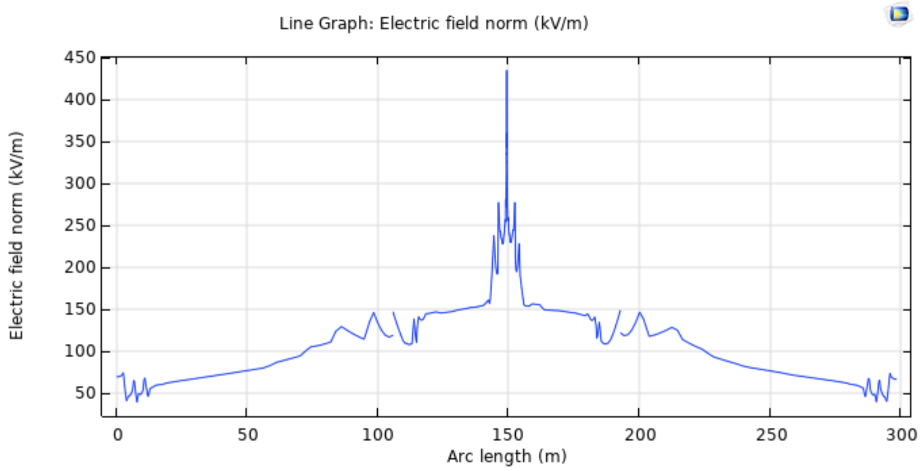


Figure 5. 79 Electric field distribution along cross-section Jethawanaramaya -30kA- Directly above at 91.2m from tip

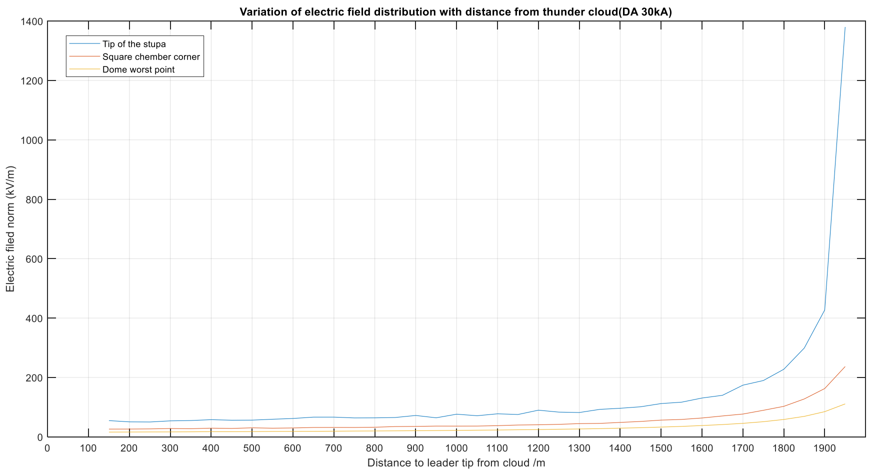


Figure 5. 80 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 80, at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, an upward leader will not initiate from those points. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

- **When the surge is on the side of the stupa**

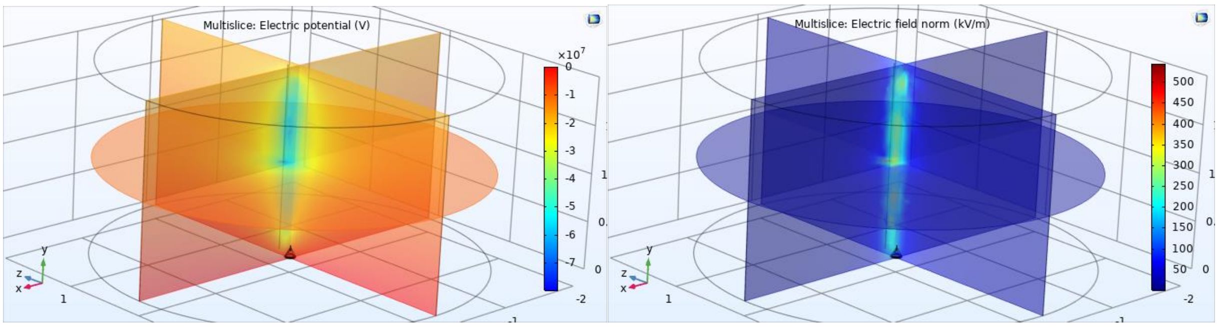


Figure 5. 81 (a) Voltage distribution for Jethawanaramaya -30kA- Directly above at 91.2m from ground (b) Electric field distribution for Jethawanaramaya -30kA- Directly above at 91.2m from ground

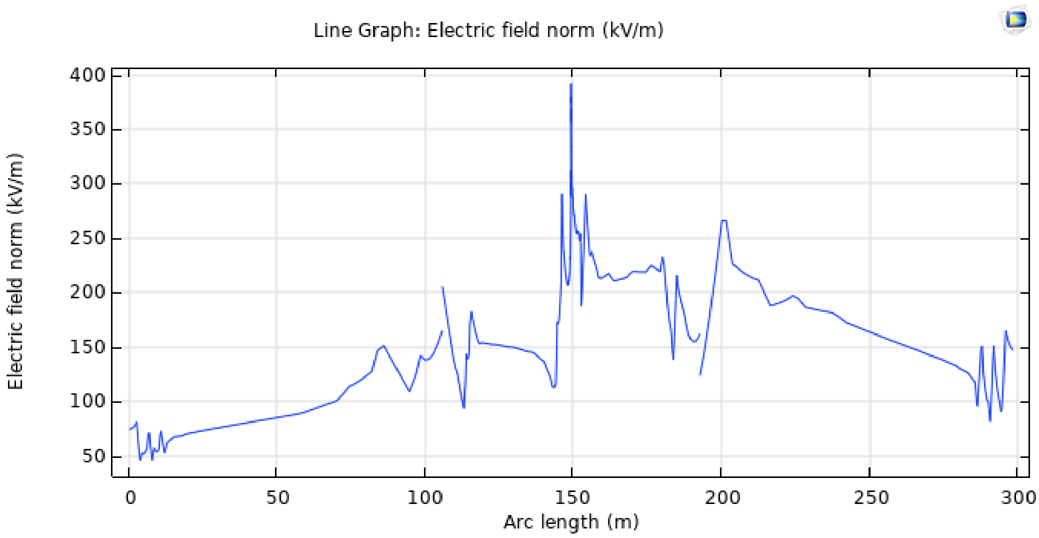


Figure 5. 82 Electric field distribution along cross-section Jethawanaramaya -30kA- Directly above at 91.2m from ground

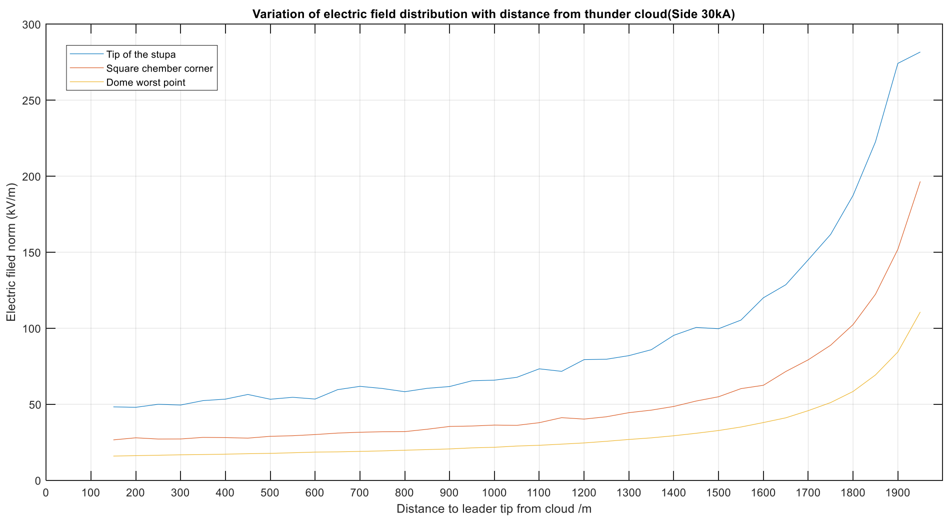


Figure 5. 83 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 82, at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, an upward leader will not initiate from those points. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

5.6.1.2 Considering 200kA surge

- **When the surge is directly above the stupa**

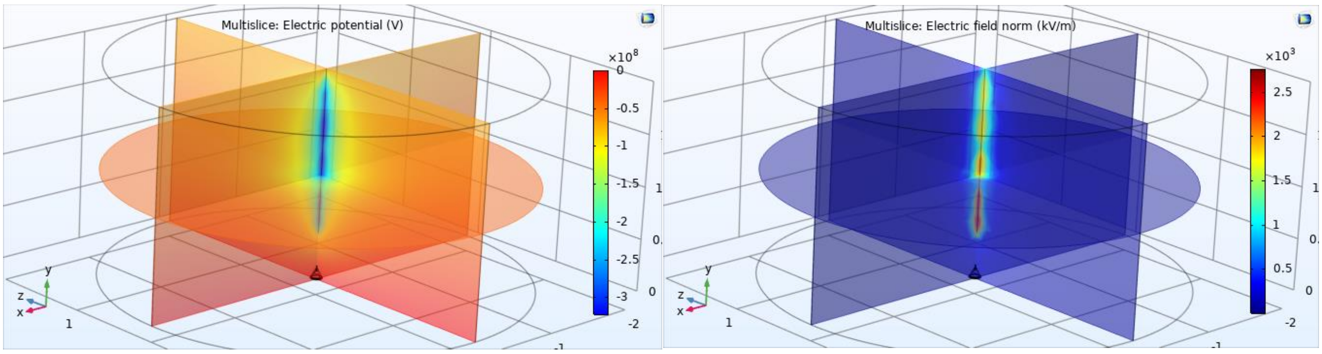


Figure 5. 84 (a) Voltage distribution for Jethawanaramaya -200kA- Directly above at 313m from tip
(b) Electric field distribution for Jethawanaramaya -200kA- Directly above at 313m from tip

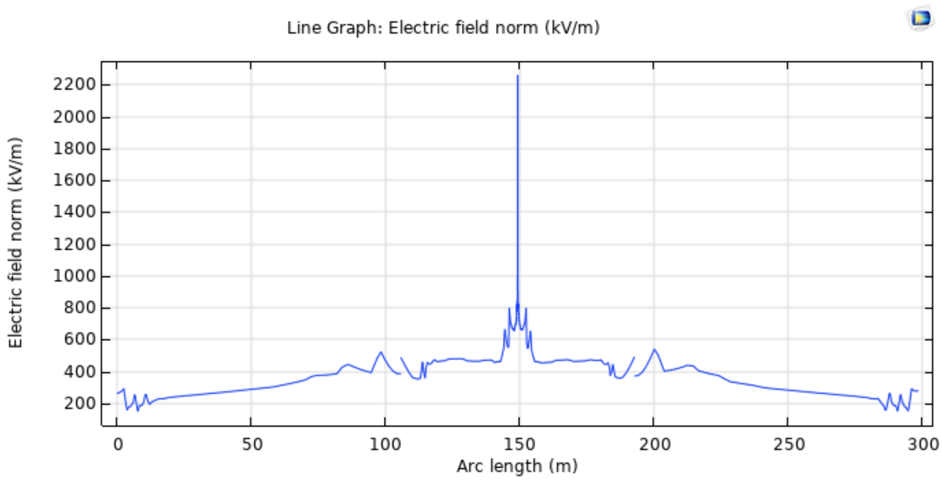


Figure 5. 85 Electric field distribution along cross-section Jethawanaramaya -200kA- Directly above at 313m from tip

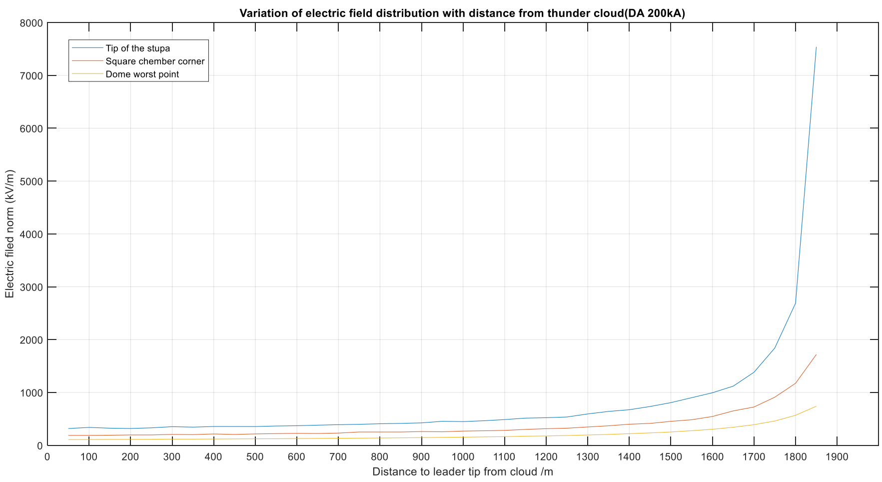


Figure 5. 86 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 86, at the tip of the stupa, an upward leader will initiate. Even if there is a possibility that an upward leader will initiate from the square chamber and dome worst points according to figure 5. 85, the downward leader will connect to the tip of the stupa since it electric field is much higher. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

- **When the surge is on the side of the stupa**

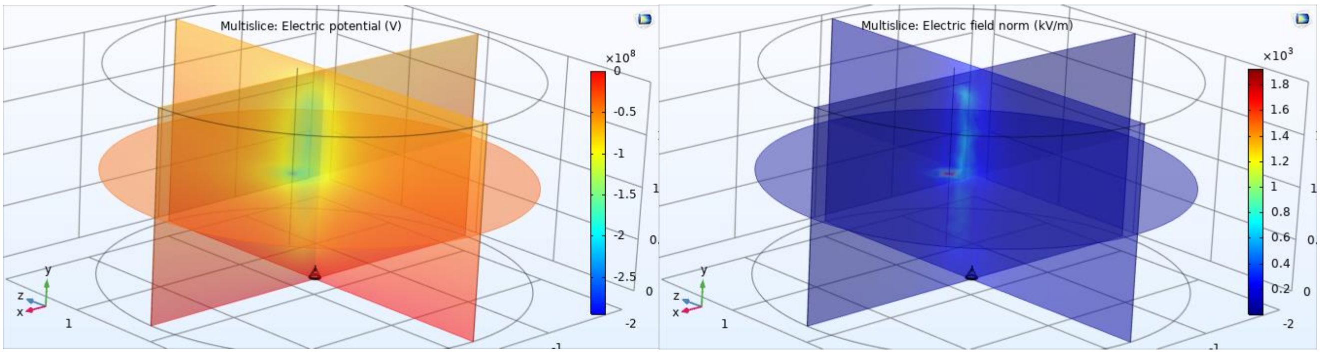


Figure 5. 87 (a) Voltage distribution for Jethawanaramaya -200kA- Directly above at 313m from tip (b) Electric field distribution for Jethawanaramaya -200kA- Directly above at 313m from tip

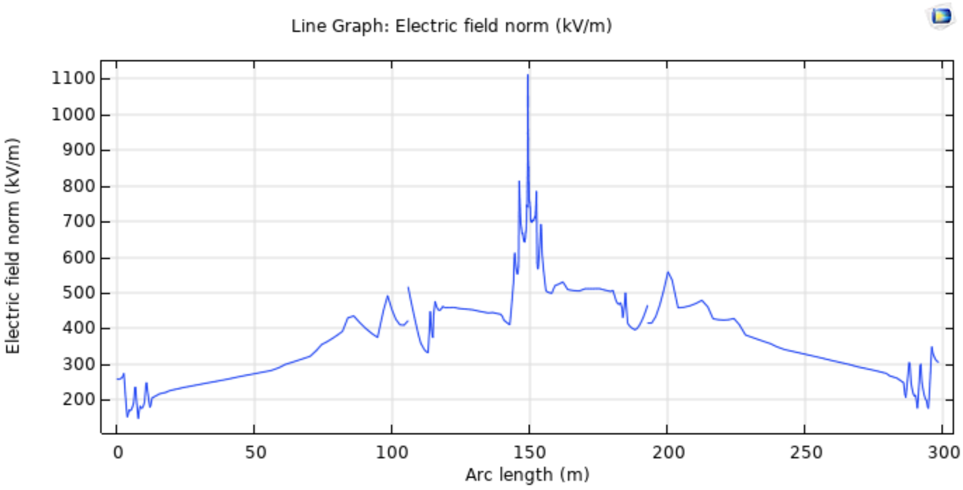


Figure 5. 88 Electric field distribution along cross-section Jethawanaramaya -200kA- Directly above at 313m from tip

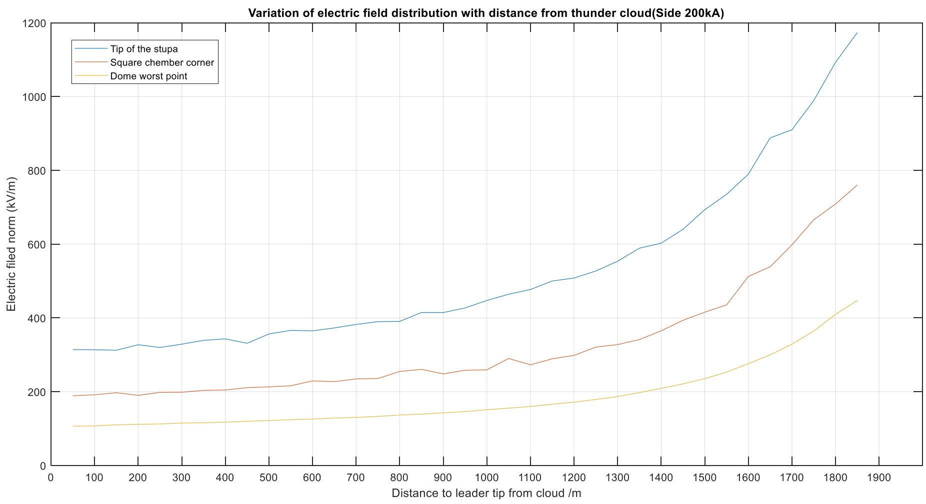


Figure 5. 89 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 89, at the tip of the stupa, an upward leader will initiate. Even if there is a possibility that an upward leader will initiate from the square chamber and dome worst points according to figure 5. 88, the downward leader will connect to the tip of the stupa since it electric field is much higher. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

5.6.3 Abayagiriya at ancient dimensions

5.6.1.1 Considering 30kA surge

- **When the surge is directly above the stupa**

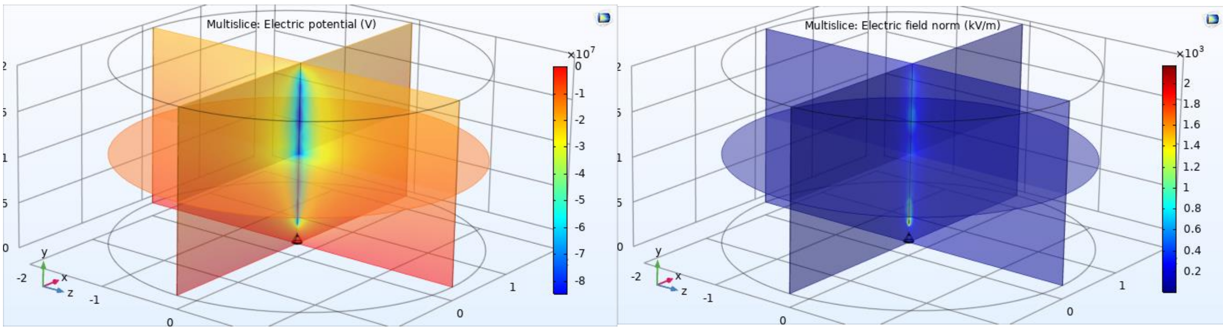


Figure 5. 90 (a) Voltage distribution for Abayagiriya-30kA- Directly above at 91.2m from tip (b) Electric field distribution for Abayagiriya -30kA- Directly above at 91.2m from tip

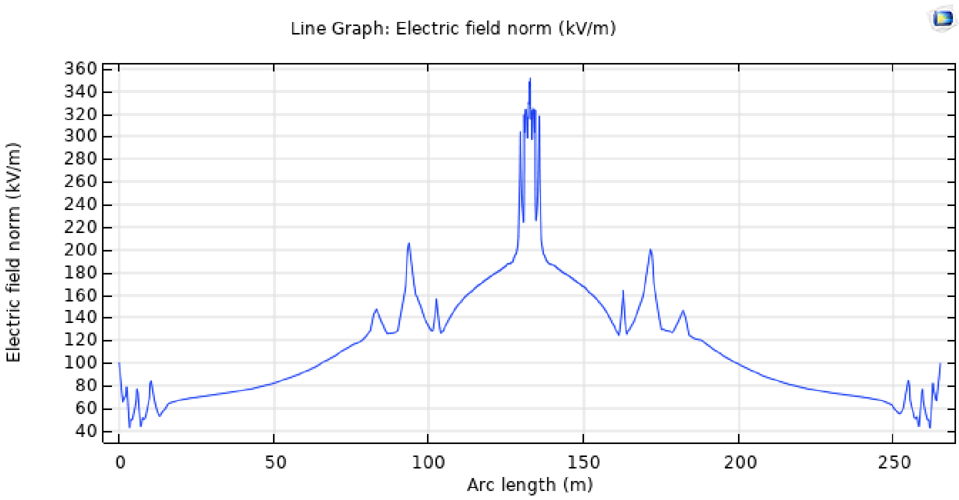


Figure 5. 91 Electric field distribution along cross-section Abayagiriya -30kA- Directly above at 91.2m from tip

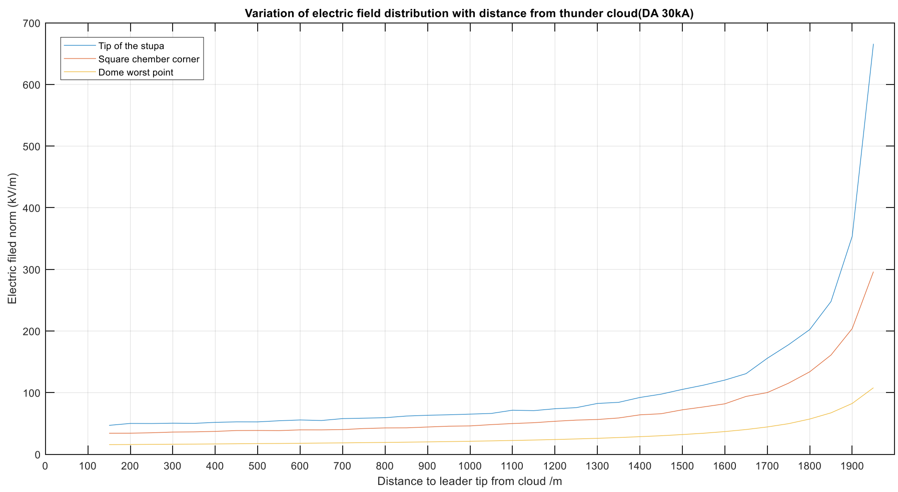


Figure 5. 92 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 91, at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, an upward leader will not initiate from those points. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

- **When the surge is on the side of the stupa**

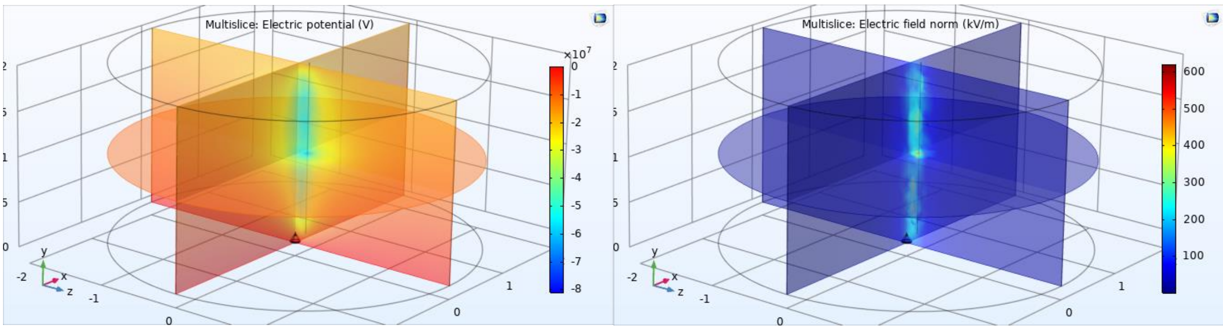


Figure 5. 93 (a) Voltage distribution for Abayagiriya a-30kA- Directly above at 91.2m from ground (b) Electric field distribution for Abayagiriya -30kA- Directly above at 91.2m from ground

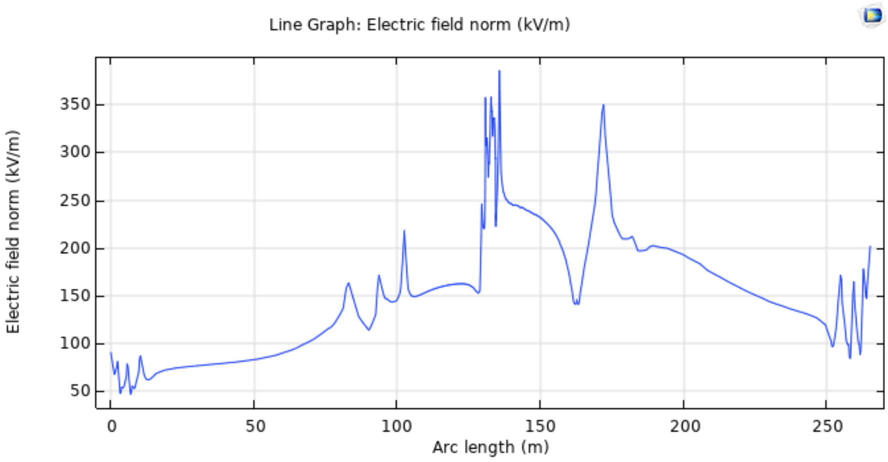


Figure 5. 94 Electric field distribution along cross-section Abayagiriya -30kA- Directly above at 91.2m from ground

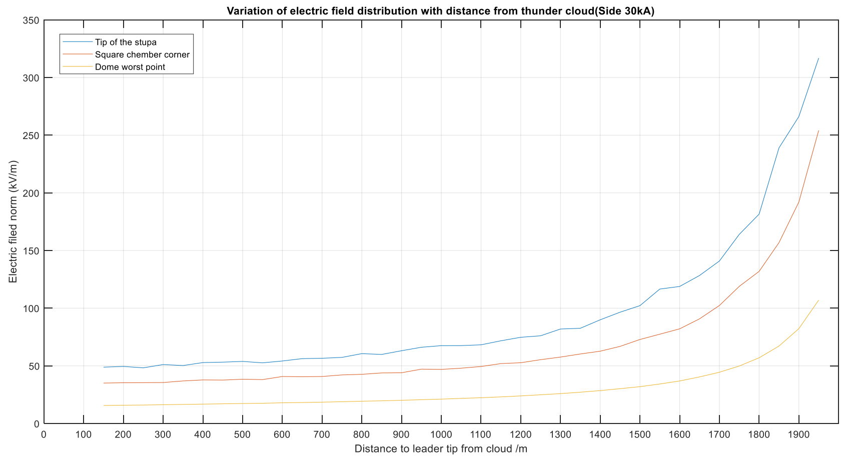


Figure 5. 95 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 95, at the tip of the stupa, an upward leader will initiate first. But according to figure 5. 94, there is a possibility that an upward leader will initiate from the square chamber corner closer to downward leader as well. Also, for the dome worst point, which is the unprotected region obtained from RSM, an upward leader will not initiate. So, it can be concluded that the tip of the stupa and square chamber corners are vulnerable to a lightning strike.

5.6.1.2 Considering 200kA surge

- **When the surge is directly above the stupa**

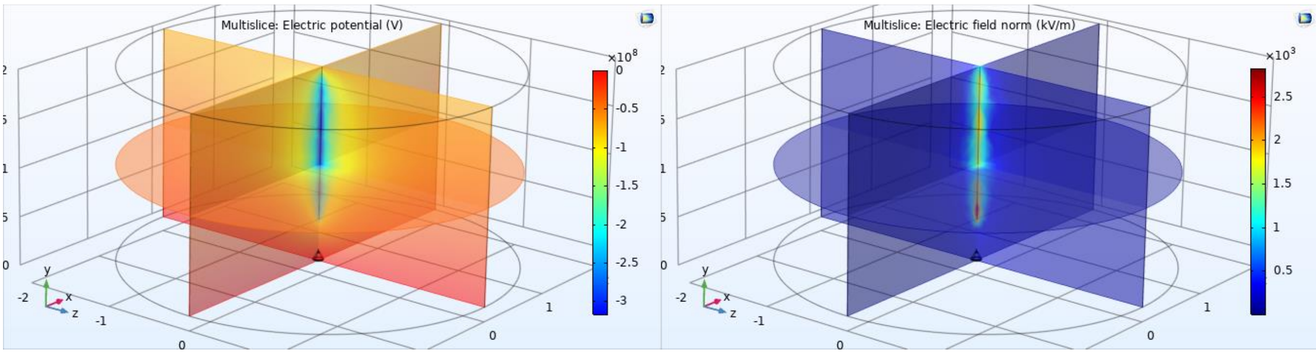


Figure 5. 96 (a) Voltage distribution for Abayagiriya -200kA- Directly above at 313m from tip (b) Electric field distribution for Abayagiriya -200kA- Directly above at 313m from tip

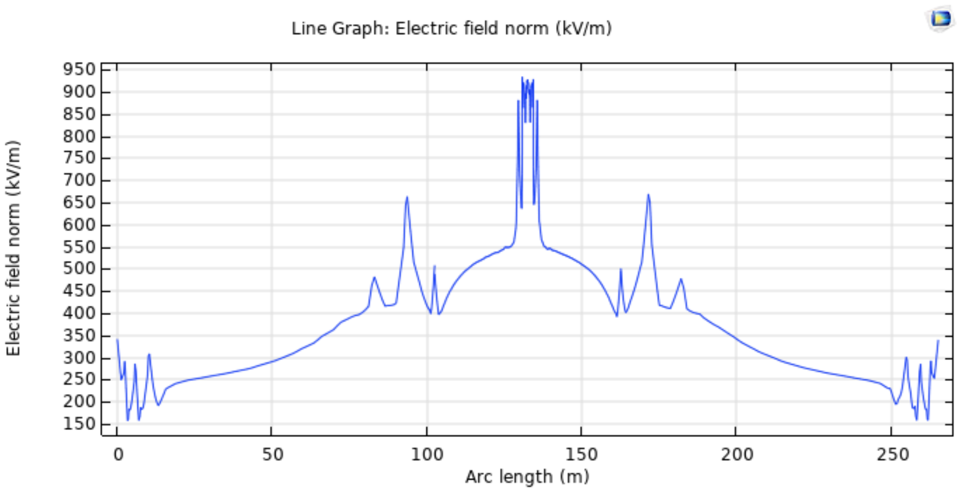


Figure 5. 97 Electric field distribution along cross-section Abayagiriya 200kA- Directly above at 313m from tip

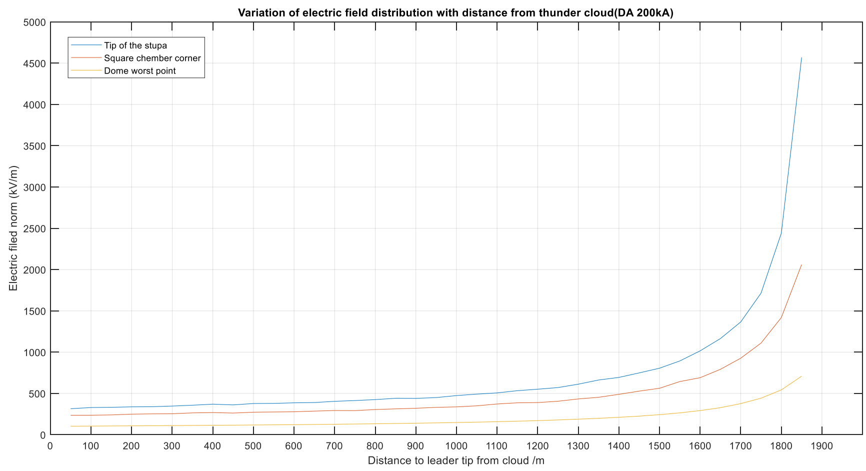


Figure 5. 98 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 98, at the tip of the stupa, an upward leader will initiate first. Even if there is a possibility that an upward leader will initiate from the square chamber and dome worst points according to figure 5. 97, the downward leader will connect to the tip of the stupa since it electric field is much higher. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

- **When the surge is on the side of the stupa**

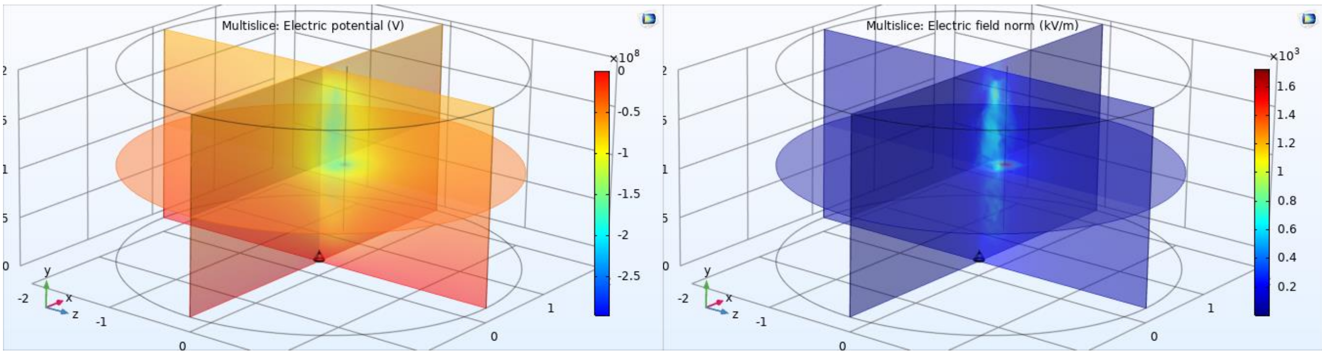


Figure 5. 99 (a) Voltage distribution for Abayagiriya -200kA- Directly above at 313m from tip
(b) Electric field distribution for Abayagiriya -200kA- Directly above at 313m from tip

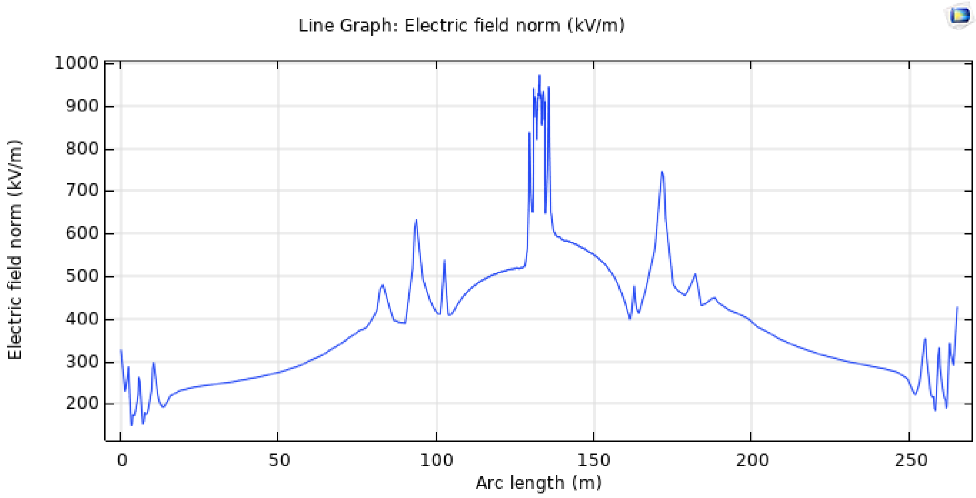


Figure 5. 100 Electric field distribution along cross-section Abayagiriya 200kA- Directly above at 313m from tip

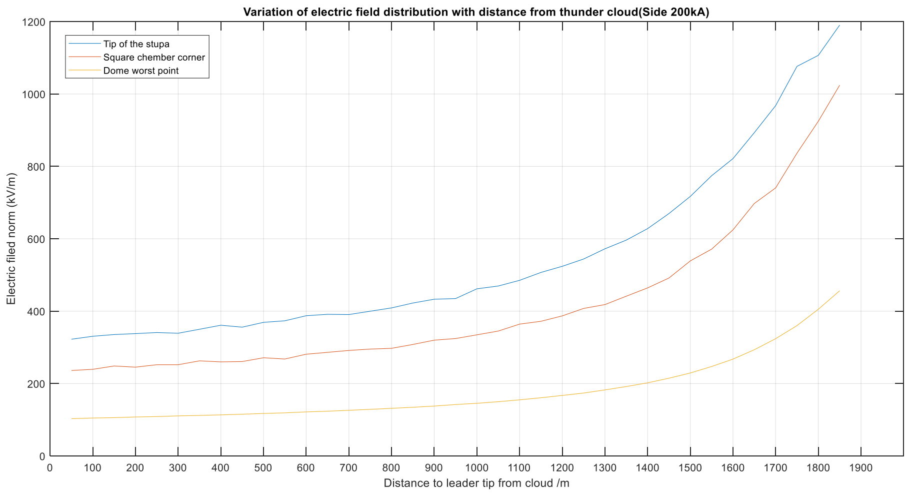


Figure 5. 101 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 101, at the tip of the stupa, an upward leader will initiate first. Even if there is a possibility that an upward leader will initiate from the square chamber and dome worst points according to figure 5. 100, the downward leader will connect to the tip of the stupa since it electric field is much higher. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

5.6.4 Mirisawetiya at ancient dimensions

5.6.1.1 Considering 30kA surge

- **When the surge is directly above the stupa**

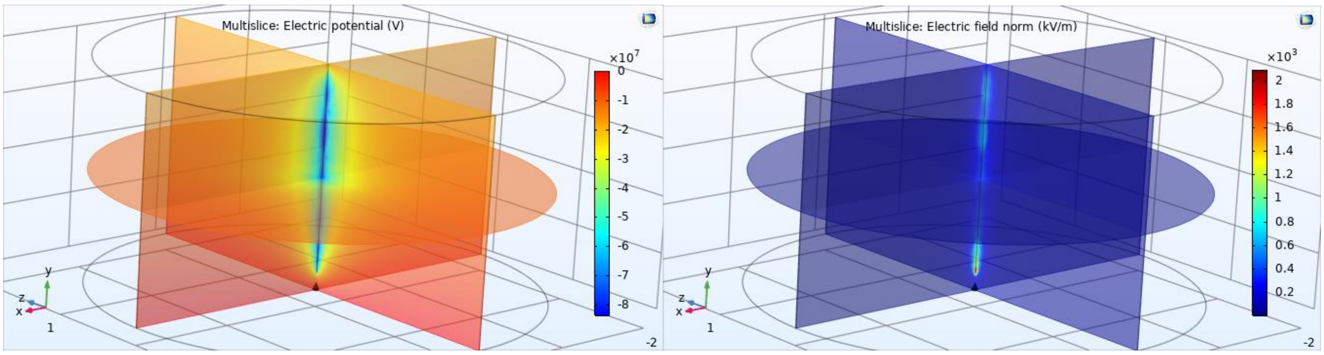


Figure 5. 102 (a) Voltage distribution for Mirisawetiya-30kA- Directly above at 91.2m from tip (b) Electric field distribution for Mirisawetiya -30kA- Directly above at 91.2m from tip

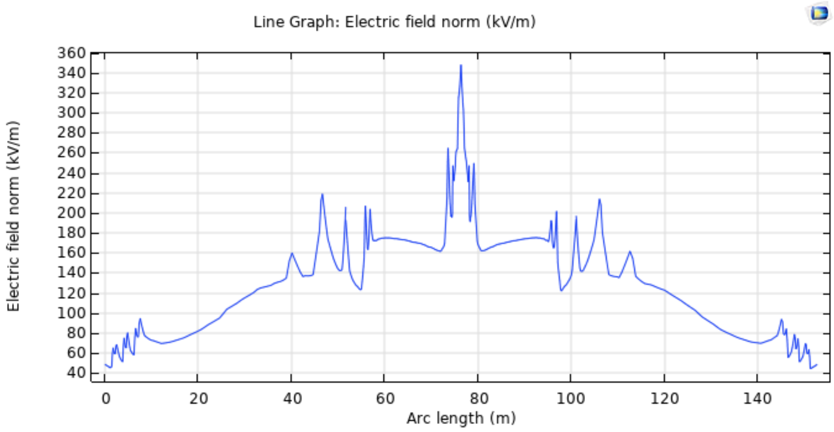


Figure 5. 103 Electric field distribution along cross-section Mirisawetiya -30kA- Directly above at 91.2m from tip

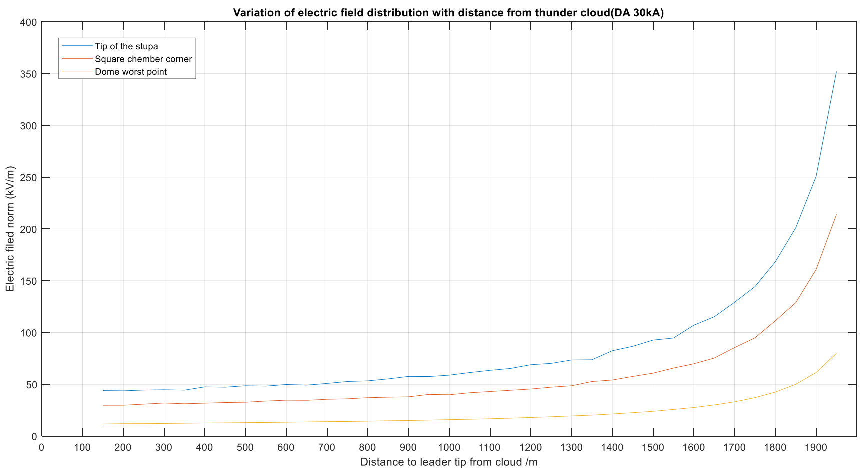


Figure 5. 104 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 103, at the tip of the stupa, an upward leader will initiate. Also, for the cases of square chamber corners and dome worst points, which is the unprotected region obtained from RSM, an upward leader will not initiate from those points. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

- **When the surge is on the side of the stupa**

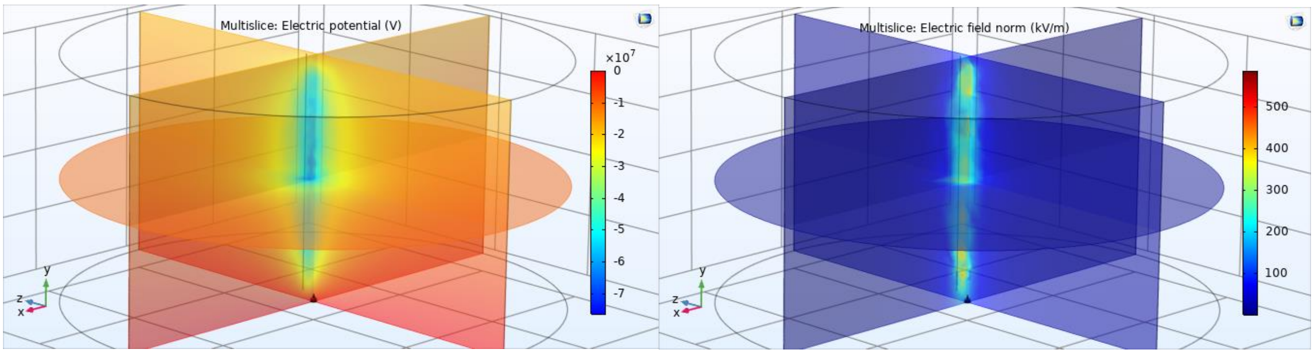


Figure 5. 105 (a) Voltage distribution for Mirisawetiya -30kA- Directly above at 91.2m from ground (b) Electric field distribution for Mirisawetiya -30kA- Directly above at 91.2m from ground

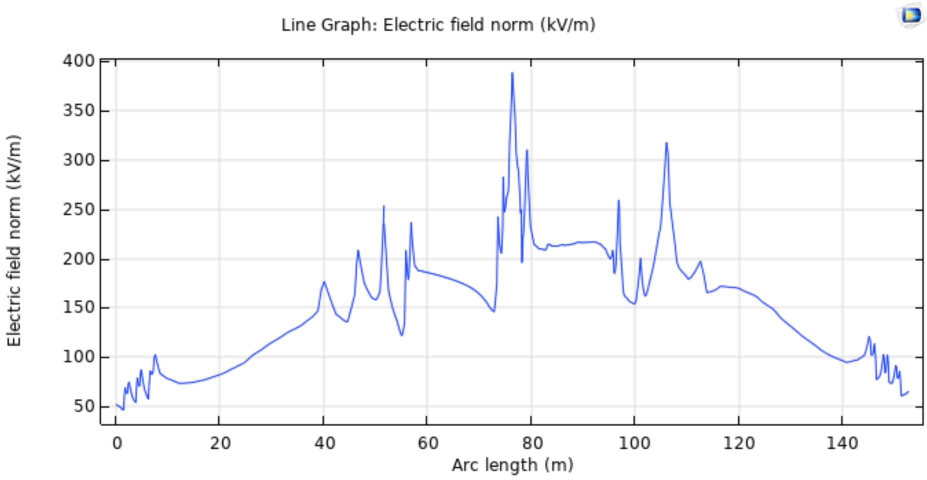


Figure 5. 106 Electric field distribution along cross-section Mirisawetiya-30kA- Directly above at 91.2m from ground

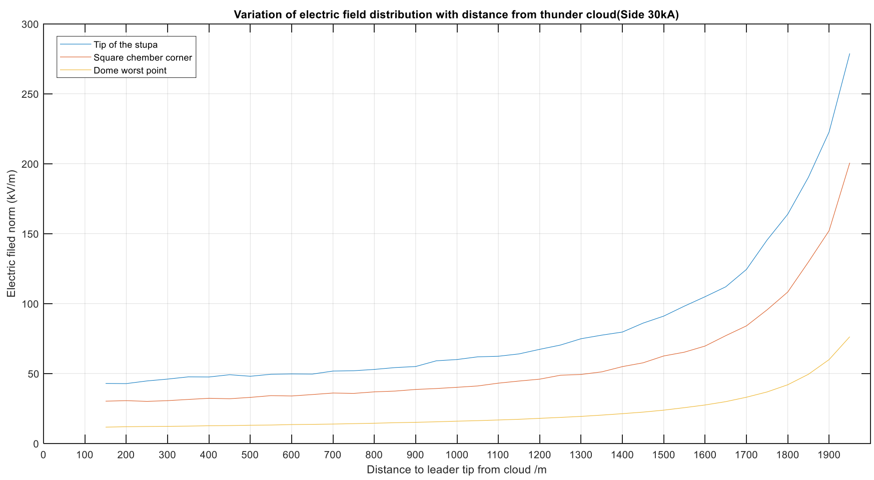


Figure 5. 107 Electric field distribution variation with the step leader length -30kA- Directly above

From the observation of figure 5. 107, at the tip of the stupa, an upward leader will initiate first. But according to figure 5. 106, there is a possibility that an upward leader will initiate from the square chamber corner closer to downward leader as well. Also, for the dome worst point, which is the unprotected region obtained from RSM, an upward leader will not initiate. So, it can be concluded that the tip of the stupa and square chamber corners are vulnerable to a lightning strike.

5.6.1.2 Considering 200kA surge

- **When the surge is directly above the stupa**

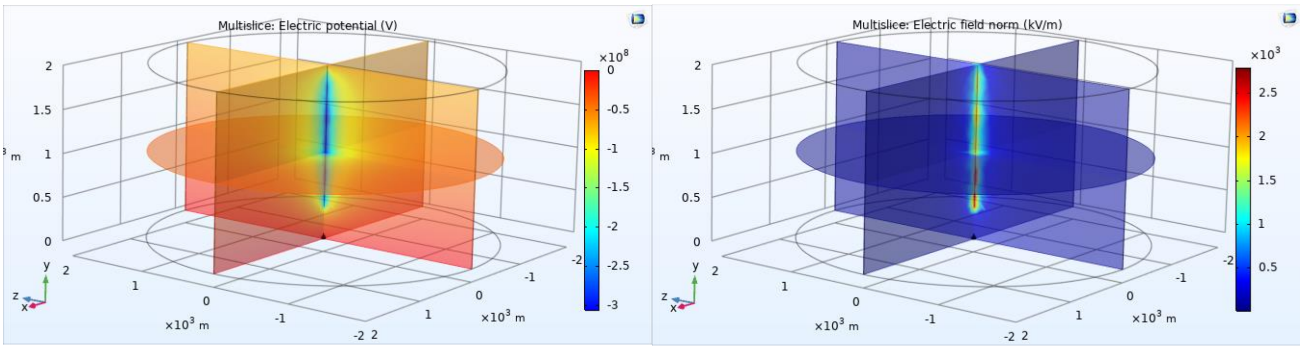


Figure 5. 108 (a) Voltage distribution for Mirisawetiya -200kA- Directly above at 313m from tip (b) Electric field distribution for Mirisawetiya 200kA- Directly above at 313m from tip

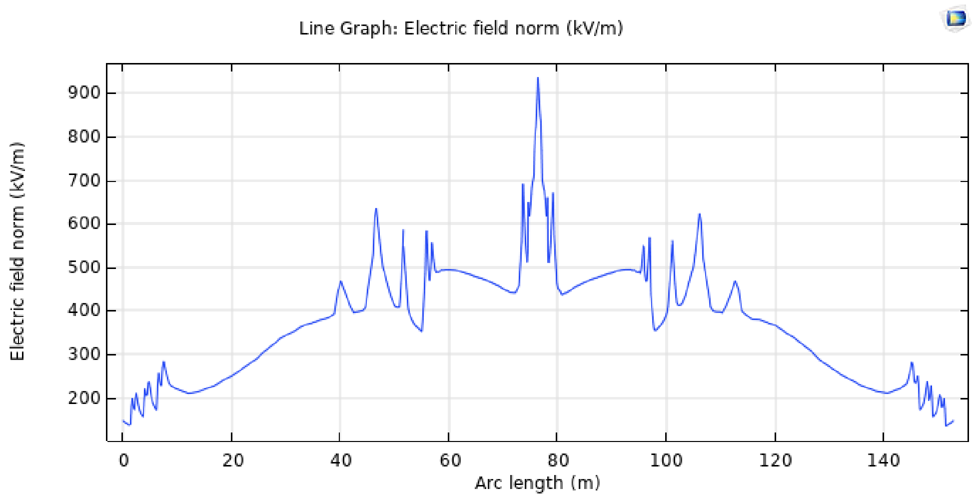


Figure 5. 109 Electric field distribution along cross-section Mirisawetiya -200kA- Directly above at 313m from tip

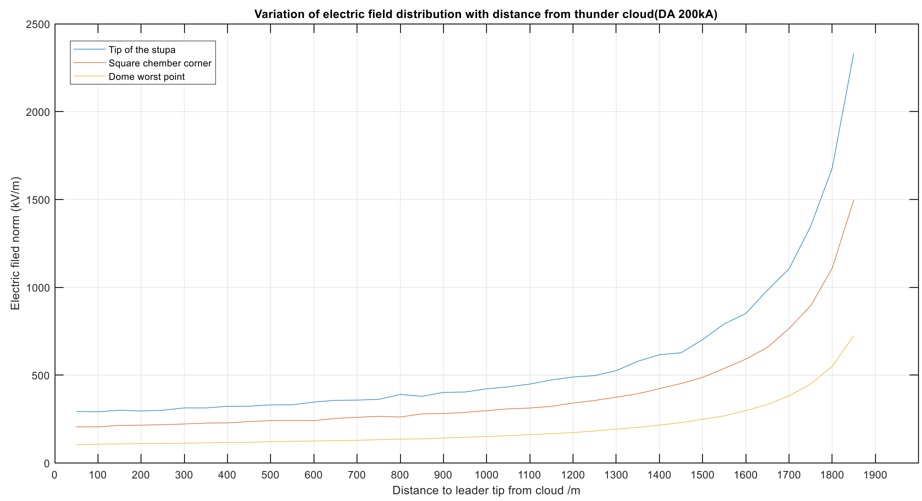


Figure 5. 110 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 11., at the tip of the stupa, an upward leader will initiate first. Even if there is a possibility that an upward leader will initiate from the square chamber and dome worst points according to figure 5. 109, the downward leader will connect to the tip of the stupa since it electric field is much higher. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

- **When the surge is on the side of the stupa**

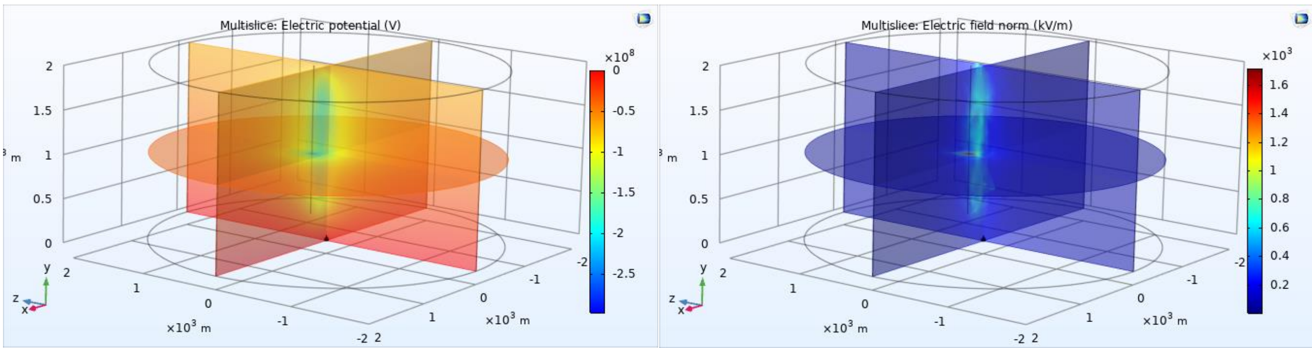


Figure 5. 111 (a) Voltage distribution for Mirisawetiya -200kA- Directly above at 313m from tip (b) Electric field distribution for Mirisawetiya -200kA- Directly above at 313m from tip

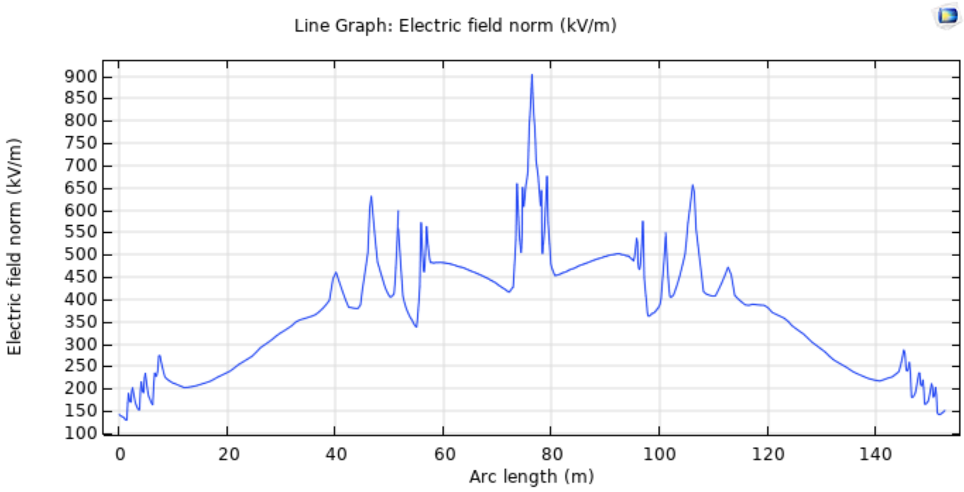


Figure 5. 112 Electric field distribution along cross-section Mirisawetiya -200kA- Directly above at 313m from tip

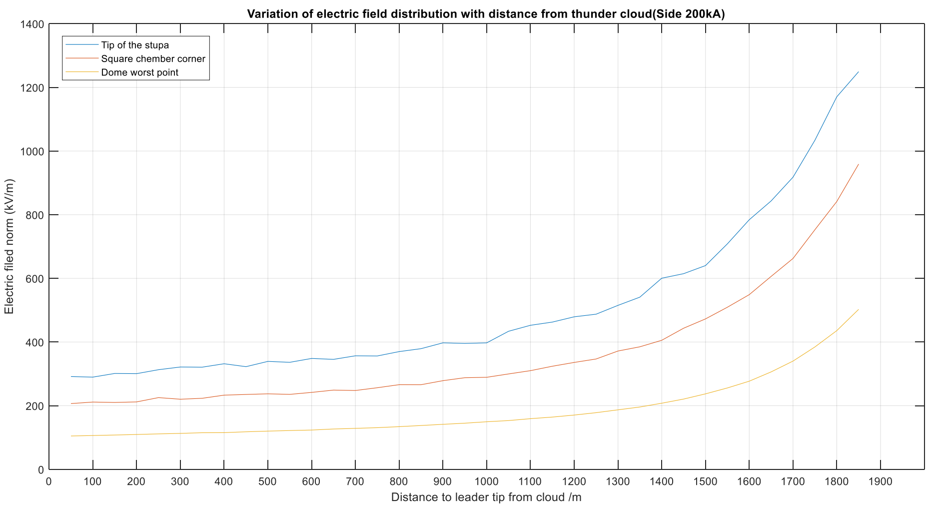


Figure 5. 113 Electric field distribution variation with the step leader length -200kA- Directly above

From the observation of figure 5. 113, at the tip of the stupa, an upward leader will initiate first. Even if there is a possibility that an upward leader will initiate from the square chamber and dome worst points according to figure 5. 112, the downward leader will connect to the tip of the stupa since it electric field is much higher. So, it can be concluded that only the tip of the stupa is vulnerable to a lightning strike.

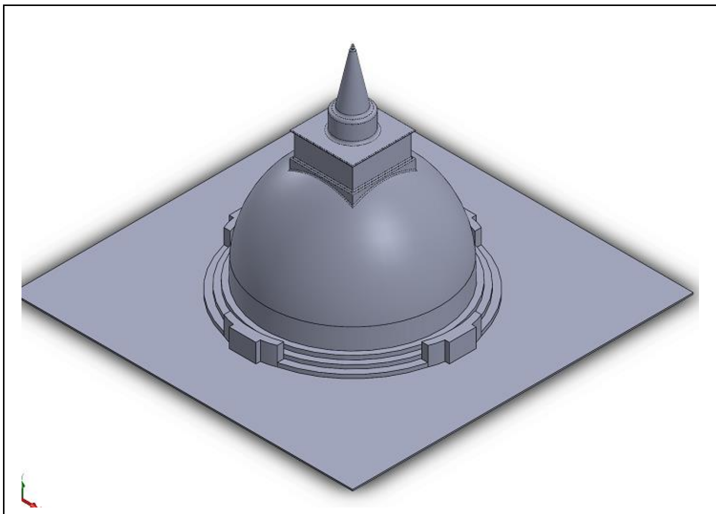
CHAPTER 6
RISK ANALYSIS FOR THE STUPA STRUCTURES INCLUDING PALACE

6. 1 INTRODUCTION

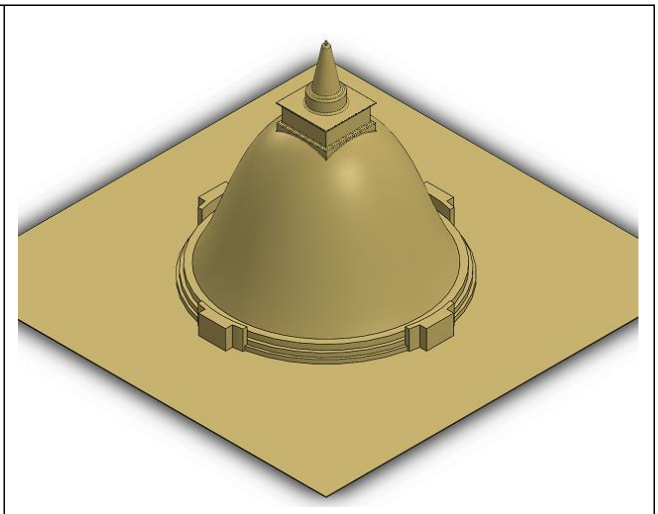
For this model, the stupa structures and the palace were placed on the same geographic region for the analysis of the lightning effects for the entire structure set.

6.2 3D MODELS OF THE ANCIENT STUPA STRUCTURES DEVELOPED USING SOLIDWORKS

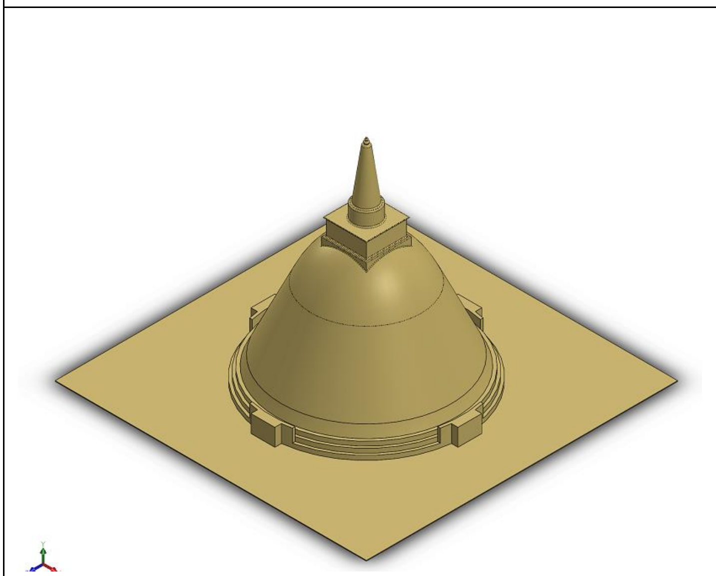
The following 3D models were developed using SOLIDWORKS. The models are generated such that they consist of complex geometrical characteristics that were assumed to be present on the ancient stupa structure while considering the estimated dimensions in the ancient stupas.



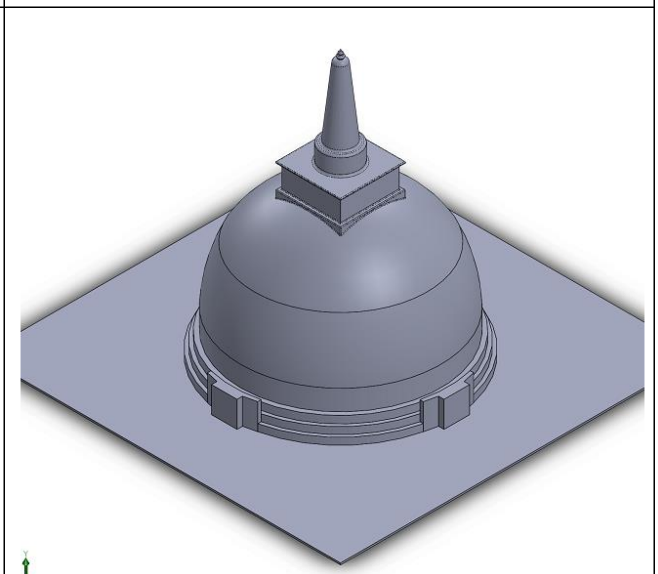
(a)



(b)



(c)

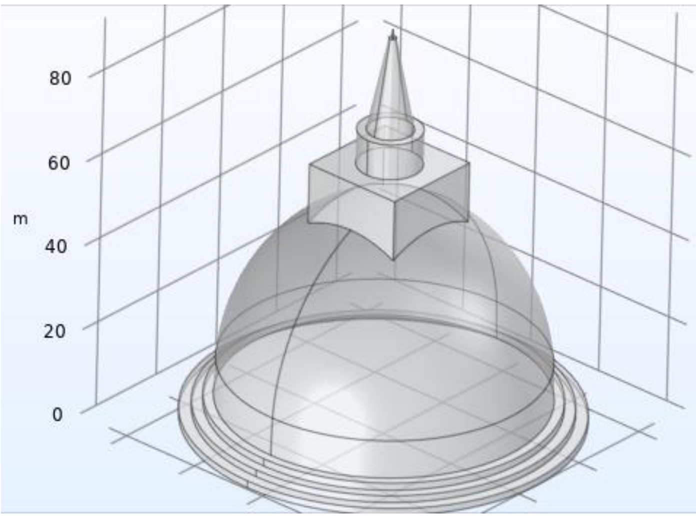


(d)

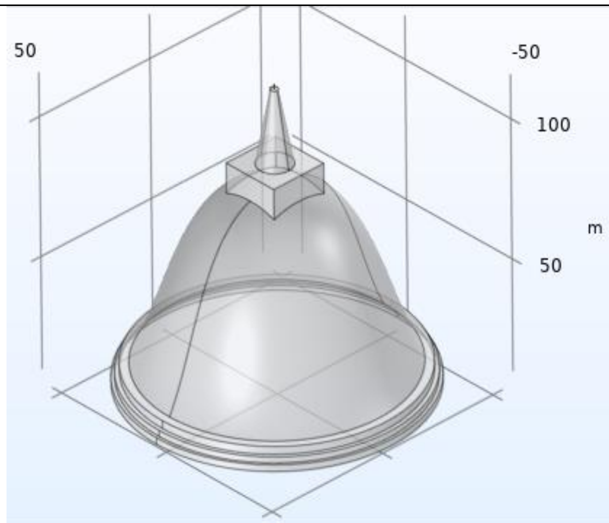
Figure 6. 1 SOLIDWORKS model of ancient (a)Ruwanweiseya, (b)Abayagiriya, (c)Jethawanaya, (d)Mirisavetiya

6. 3 3D MODELS OF THE ANCIENT STUPA STRUCTURES DEVELOPED USING COMSOL

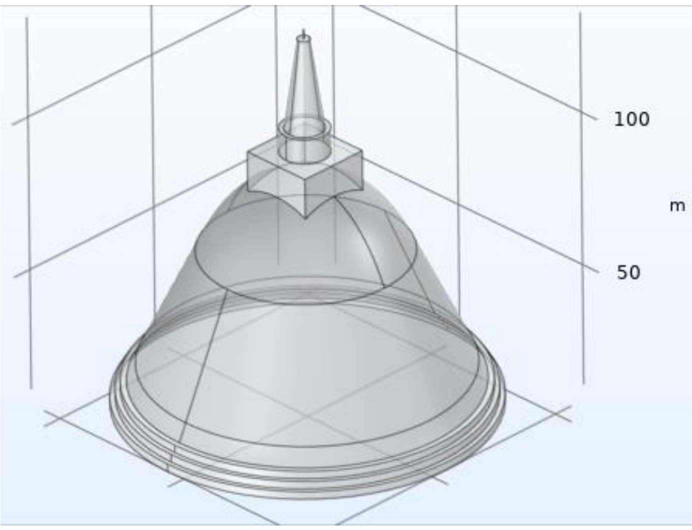
The following 3D models were developed using COMSOL Multiphysics engine for the analysis of electrical field distribution,



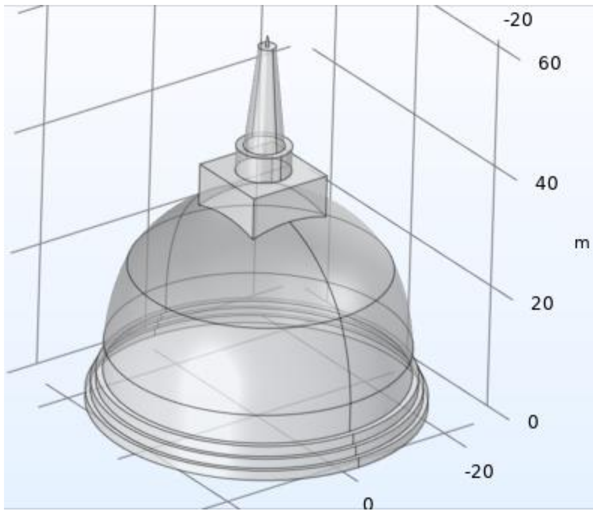
(a)



(b)



(c)



(d)

Figure 6. 2 COMSOL model of ancient (a)Ruwanweliseya, (b)Abayagiriya, (c)Jethawanaya, (d)Mirisavetiya

6.4 APPLICATION OF PROTECTIVE ANGLE METHOD FOR THE ANCIENT STUPA STRUCTURES

This method is also known as geometrical modeling. The analysis performed for each of the stupa structures are shown in the following subsections

6.4.1 RUWANWELISEYA

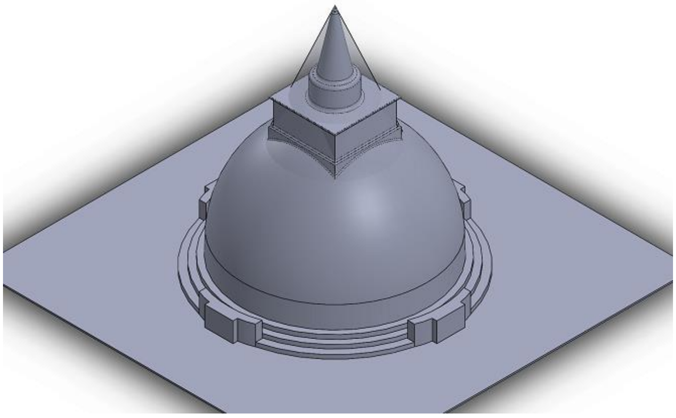


Figure 6. 3 Protective angle method applied to Ruwanweliseya stupa

6.4.2 ABAYAGIRIYA

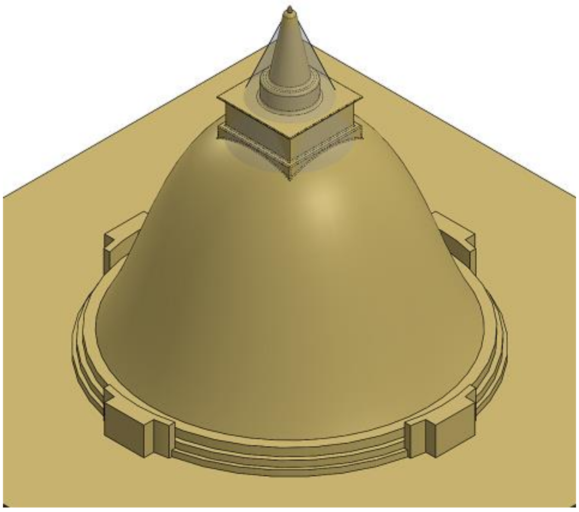


Figure 6. 4 Protective angle method applied to ancient Abayagiriya stupa

6.4.3 JETHAWANARAMAYA

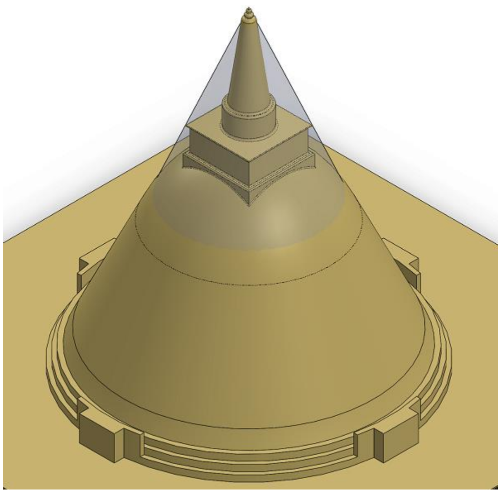


Figure 6. 5 Protective angle method applied to ancient Jethawanaramaya stupa

6.4.4 MIRISAVETIYA

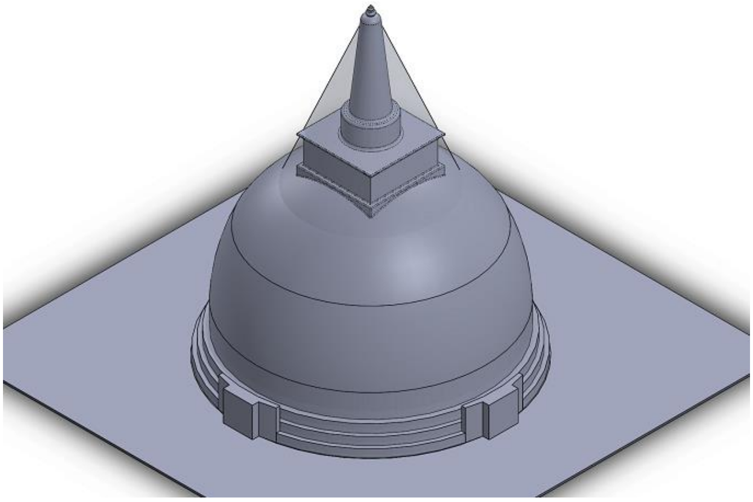


Figure 6. 6 Protective angle method applied to ancient Mirisavetiya stupa

Upon observation of the results of the protective angle method. With the height of the stupa structure. This analytical method becomes obsolete.

6.5 RISK ANALYSIS USING ROLLING SPHERE METHOD

This method is also known as the electro geometrical model. The analysis performed for each of the stupa structures are shown in the following subsections. The regions with the lightning risk are also shown in the following figures.

6.5.1 RUWANWELISEYA

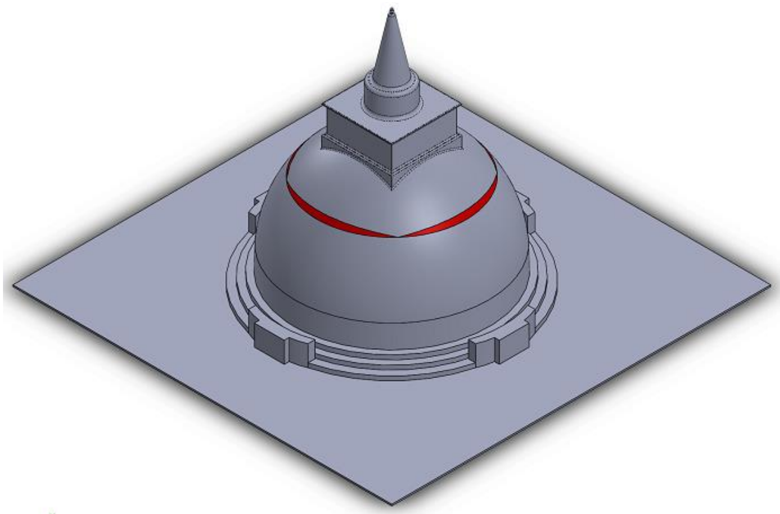


Figure 6. 7 Unprotected regions obtained from Rolling sphere method- ancient Ruwanweliseya stupa

6.5.2 ABAYAGIRIYA

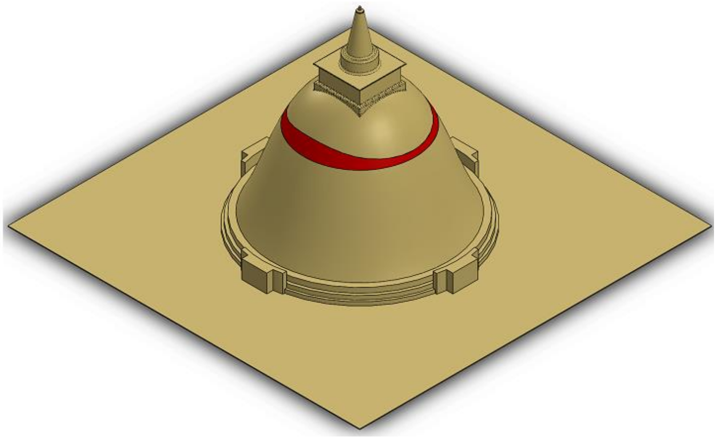


Figure 6. 8 Unprotected regions obtained from Rolling sphere method- ancient Abayagiriya stupa

6.5.3 JETHAWANARAMAYA

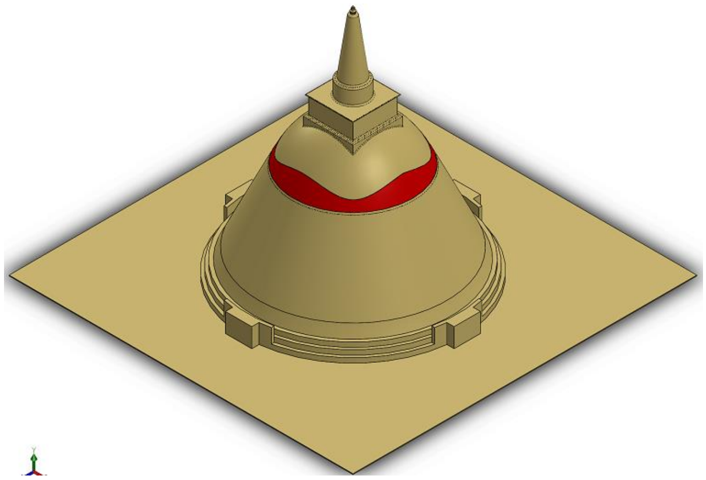


Figure 6. 9 Unprotected regions obtained from Rolling sphere method- ancient Jethawanaya stupa

6.5.4 MIRISAVETIYA

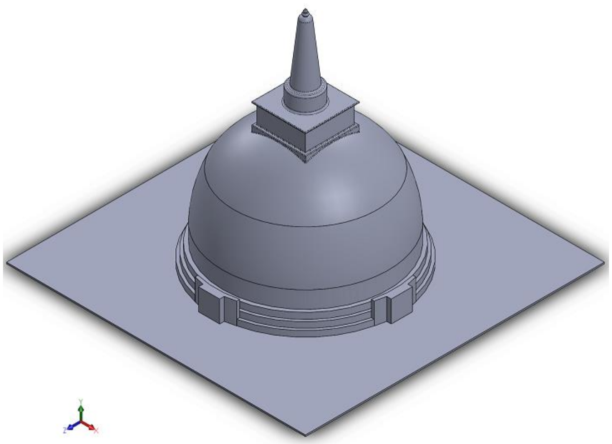


Figure 6. 10 Unprotected regions obtained from Rolling sphere method- ancient Mirisavetiya stupa

6.6 MODIFIED ROLLING SPHERE METHOD

Although the modified rolling sphere method is not included in the lightning standards, it can be used to determine the protective regions while considering the upward leader generation in the stupa structure. The upward cone dimensions can be calculated as follows

$$\textbf{Cone radius} \quad L_{up} = \frac{0.054hI - 0.178h + 0.124l + 1.057}{3.02 - 0.19h}$$

$$\textbf{Cone height} \quad H_{up} = 0.054hl + 0.87h + 0.124l + 0.37$$

Where,

h - Height of the lightning rod(m)

I - Lightning current(kA)

6.6.1 RUWANWELISEYA

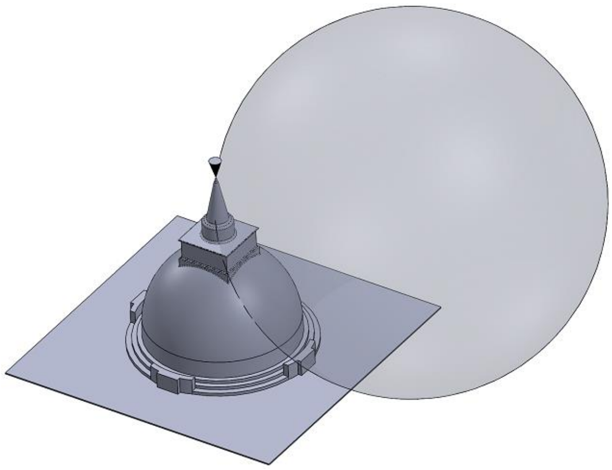


Figure 6. 11 Modified Rolling sphere method application to ancient Ruwanweliseya stupa

6.6.2 ABAYAGIRIYA

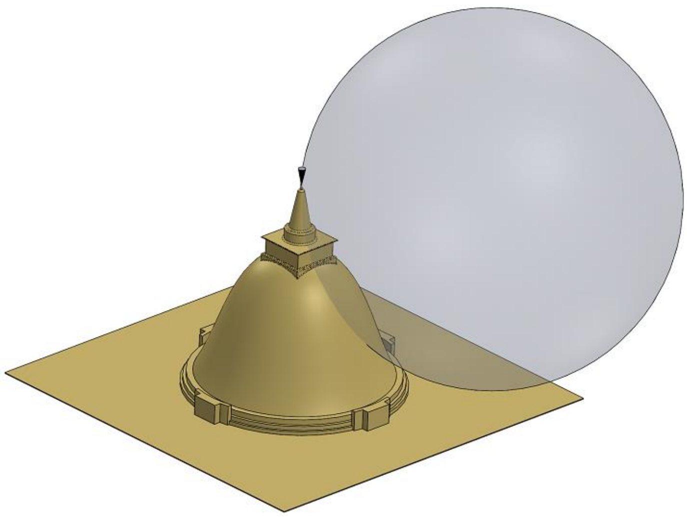


Figure 6. 12 Modified Rolling sphere method application to ancient Abayagiriya stupa

6.6.3 JETHAWANARAMAYA

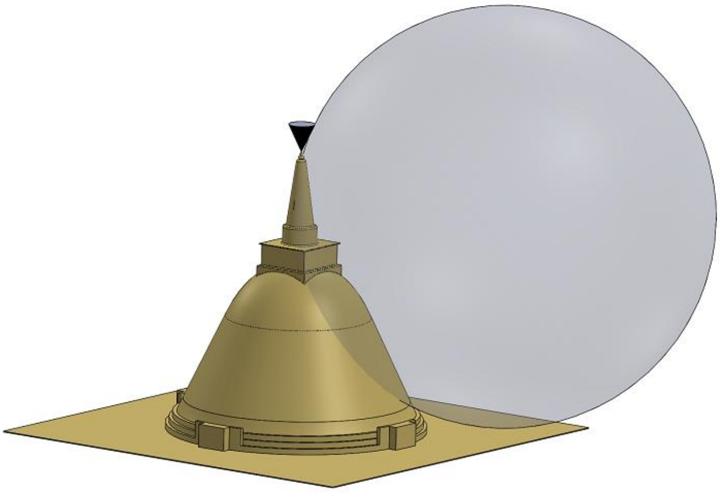


Figure 6. 13 Modified Rolling sphere method application to ancient Jethawanaramaya stupa

6.6.4 MIRISAVETIYA

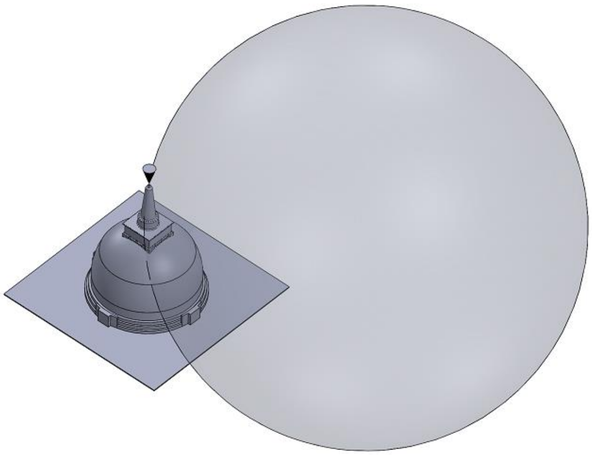


Figure 6. 14 Modified Rolling sphere method application to ancient Mirisavetiya stupa

Based on the analysis of the ancient stupa structures, they are protected according to the modified rolling sphere method.

6.7 COMSOL MODELS FOR ANCIENT STUPA STRUCTURES WITH KING VIJAYABA PALACE

According to the ancient myths, king Vijayaba's citadel was protected from lightning due to stupa structures. They believed these stupa structures were built around the king's palace to ensure the lightning protection of the king's palace.

This study was done to clarify the truth behind these stories. Coordinates of the stupa structures and palace were taken from the google map.

Ruwanveliseya	8.3500^0N	80.3964^0E
Mirisavetiya	8.3450^0N	80.3890^0E
Abayagiriya	8.3709^0N	80.3953^0E
Jethawanaramaya	8.3513^0N	80.4037^0E
Citadel	8.3558^0N	80.3949^0E

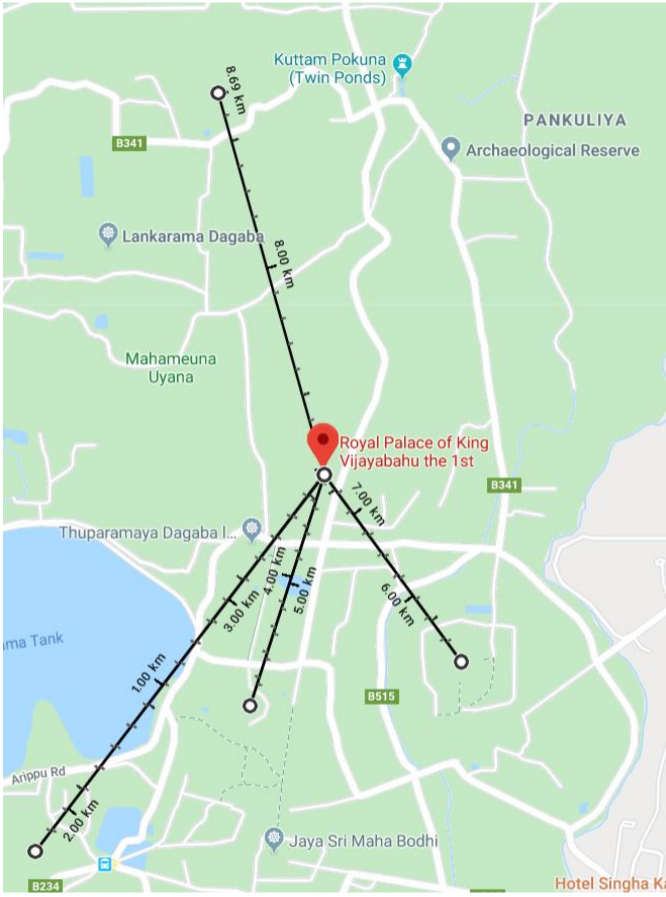


Figure 6. 15a: Geographical locations of the stupas and the citadel

By using COMSOL Multiphysics, models of stupa structures and palace were developed, and charge distribution was analyzed. For the worst-case scenario 200kA lightning was considered.

Figure 6. 16b: COMSOL Model with the stupas and the citadel

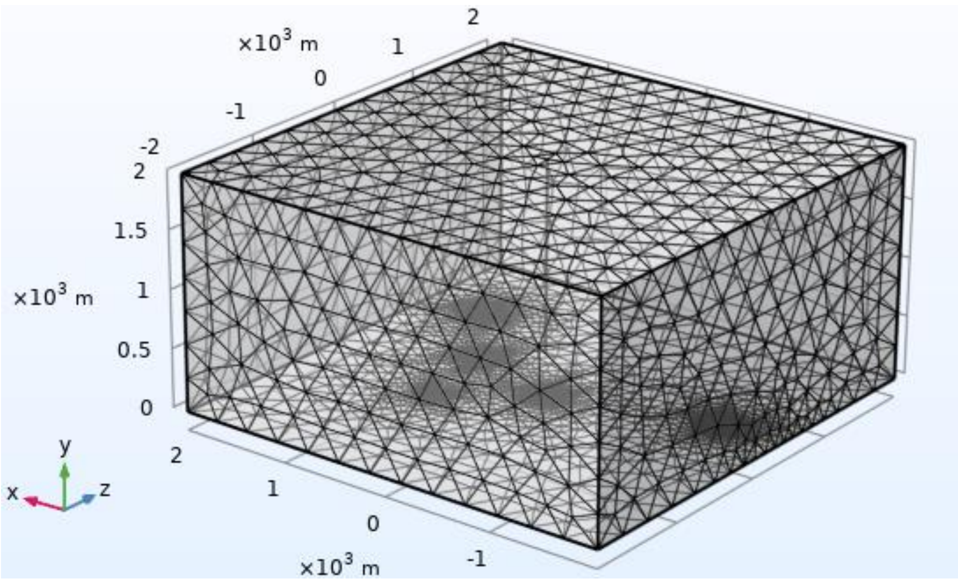


Figure 6. 17c-Generated Mesh with the citadel and other four stupas

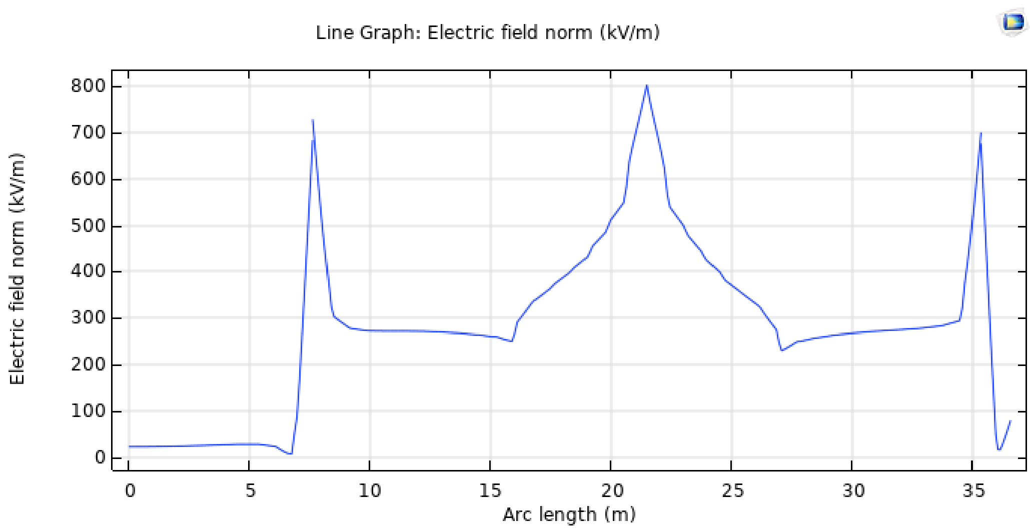


Figure 6. 18 Variation of the electric field along the citadel tower cross-section

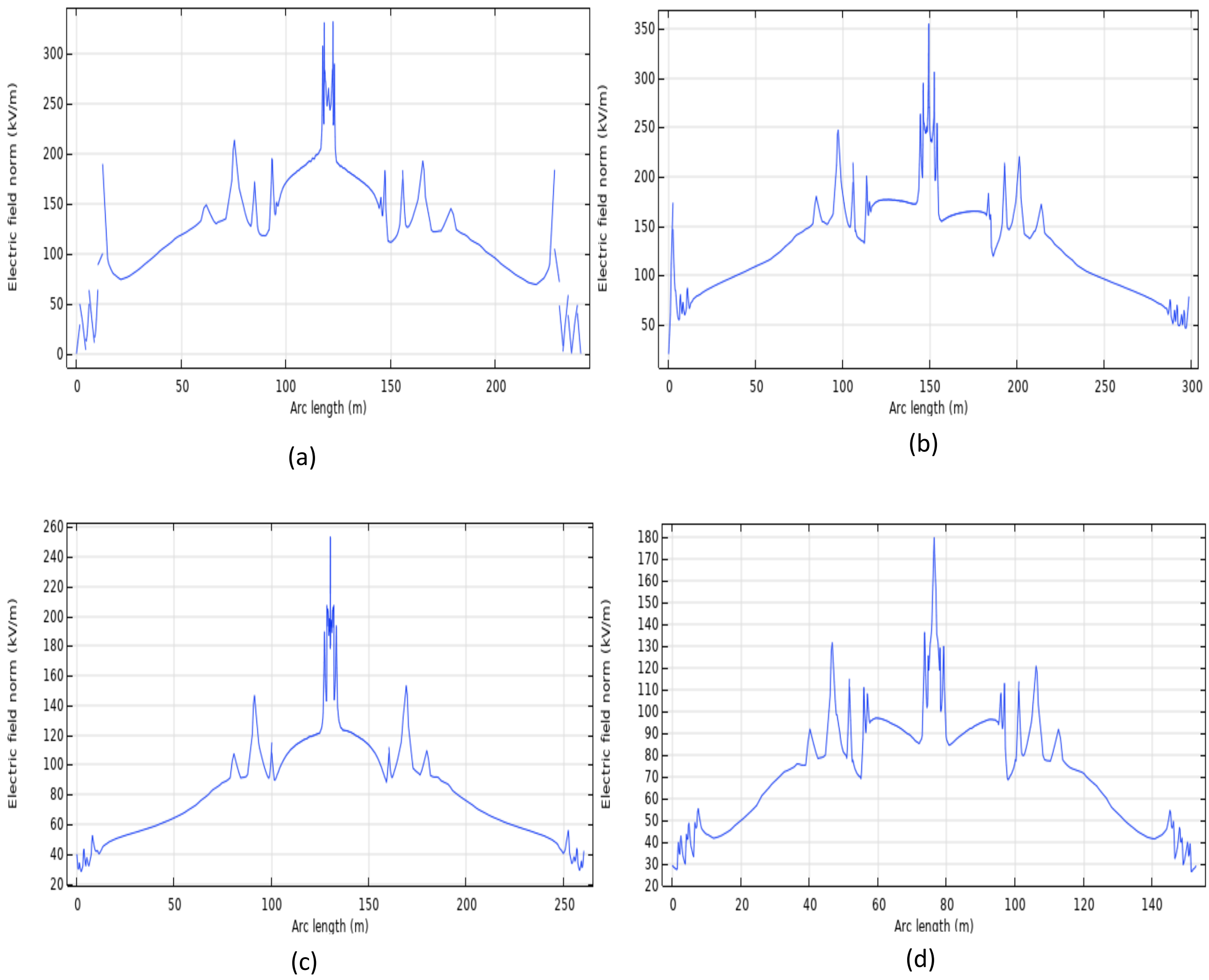


Figure 6. 19 Electric field distribution along the surface of (a) Ruwanwaliseya, (b) Jethawanaramaya, (c) Abayagiriya (d) Mirisawetiya when a 200kA leader is directly 313m above the citadel

According to figure 6. 17, an upward leader will be initiated from citadel towers when a downward leader is at 313m directly above the citadel. For Ruwanwaliseya and Jethawanaramaya, upward leaders will be initiated from the top of the stupas according to the figure 6. 18 (a) and (b). But for Abayagiriya and Mirisawetiya, the electric field intensity is not adequate for an upward leader generation. Although upward leaders generated from two of the stupas, these may not be powerful enough to draw the downward leader away from the citadel.

From these observations gathered by considering the worst case scenario of 200kA lightning which is also the rarest type of lightning, it can be stated that the stupas will not provide adequate lightning protection for the citadel. Based on the analysis done by using the COMSOL, it can be concluded that these stories are false.

CHAPTER 7
DISCUSSION

Based on the analysis done by using COMSOL lightning striking probabilities to the stupa structures along the cross section were calculated by using following formulas.

$$\text{probability of strike to the structure} = \text{probability of lightning} \times \text{probability of striking to the stupa}$$

PROBABILITY OF LIGHTNING

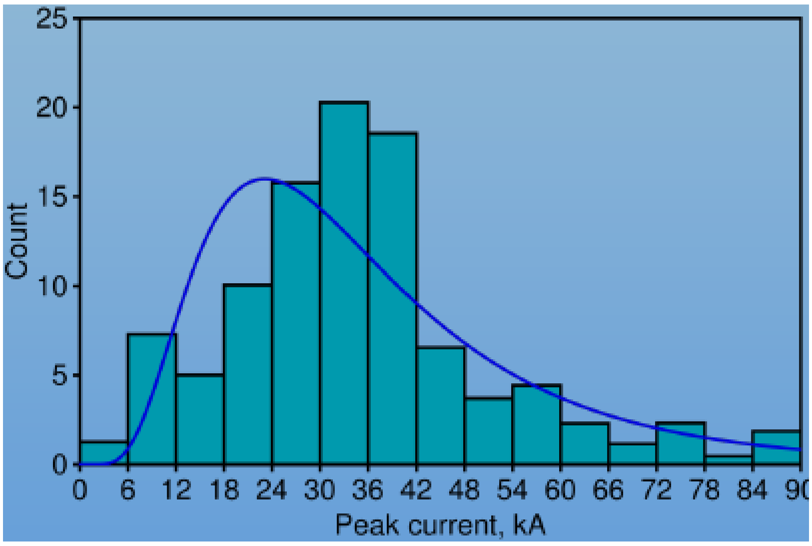


Figure 7. 1 Probability distribution function of first negative stroke

Probability distribution function is given by,

$$f(I) = \left(\frac{1}{\sqrt{2\pi}\sigma_{in} I}\right) e^{\frac{-(\ln I/\bar{I})^2}{2\sigma_{in}^2}} \qquad \text{-------- (A)}$$

Where,

$$I < 20kA \quad \bar{I} = 61.1kA \quad \sigma_{in} = 1.33$$
$$I > 20kA \quad \bar{I} = 33.3kA \quad \sigma_{in} = 0.605$$

And the corresponding probabilities for the typical case and worst case are,

for 30kA = 0.0122
for 200kA = 0.000023058
Using above equation, probability distribution was calculated for lightning currents from 10kA to 200kA in 10kA steps.

PROBABILITY OF LIGHTNING DAMAGE TO THE STRUCTURE BY USING COMSOL ANALYSIS

Then COMSOL software was live linked to MATLAB. Discrete points along a surface line as shown in figure 7. 2 which goes through the top of the stupa and pair of square chamber corners was considered. In that line number of points that exceed 300kV/m electric field was counted using MATLAB when step leader is directly above and side of each stupa.

$$probability\ of\ striking\ to\ the\ line\ = \frac{No.of\ discrete\ ponts\ along\ the\ line\ considered}{Total\ discreate\ points} \quad \text{---- (B)}$$

Probability of strike to the stupa on the line considered for each lightning current was calculated by multiplying (A) and (B) since they are independent events.

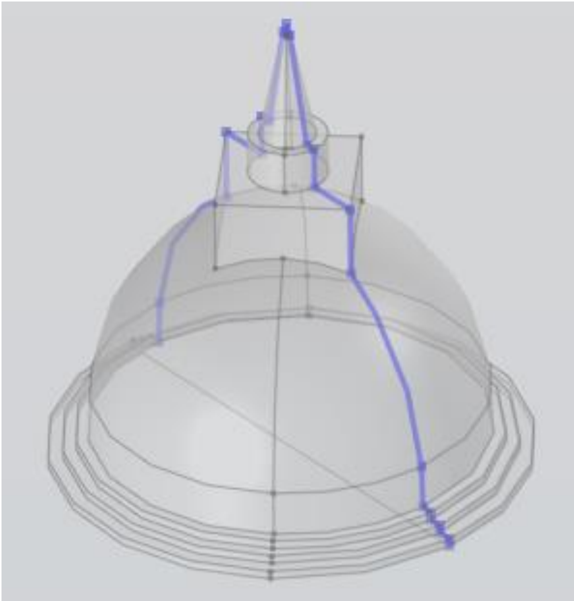


Figure 7. 2 Surface line on the stupa

Probability values for each stupa at different lightning currents and for both directly above and side strikes are shown in following figures.

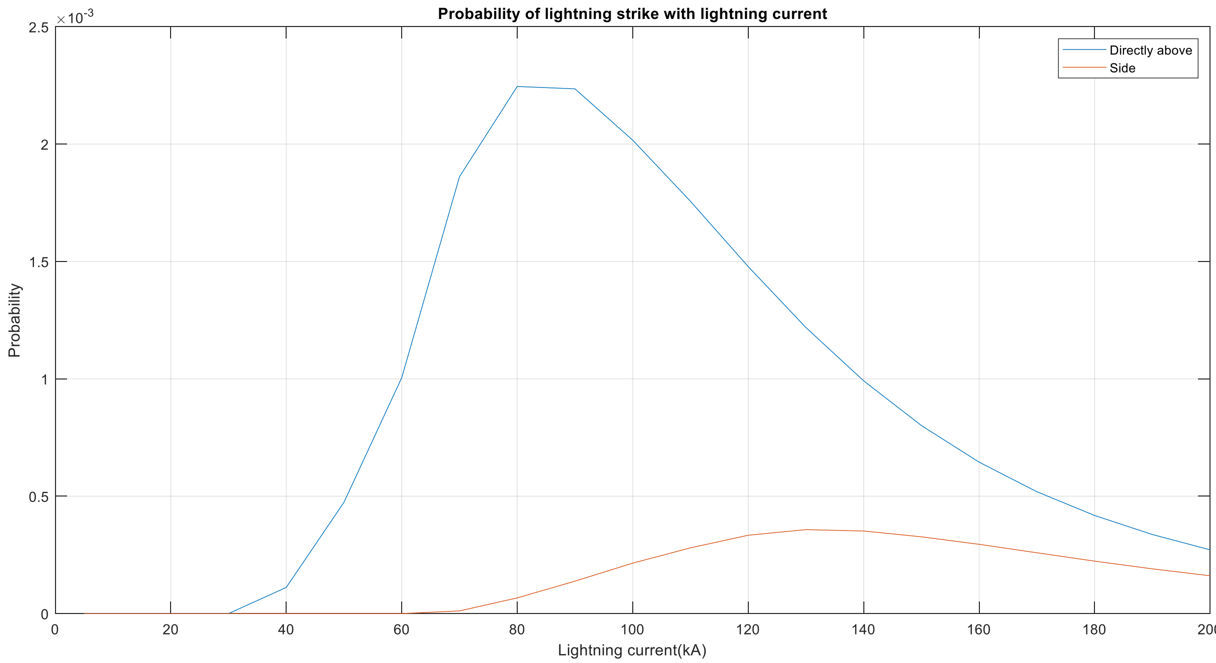


Figure 7. 3 Probability of lightning strike to Ruwanwaliseya stupa at present dimensions

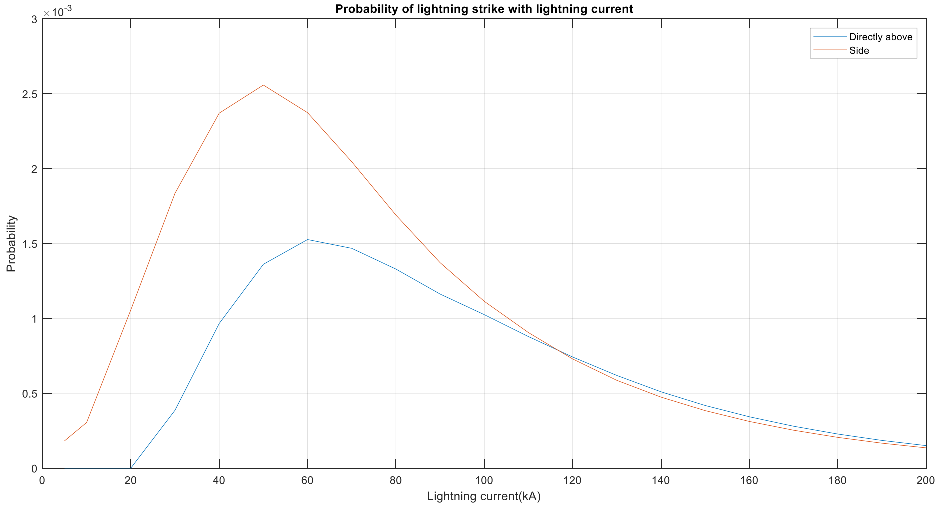


Figure 7. 4 Probability of lightning strike to Abayagiriya stupa at present dimensions

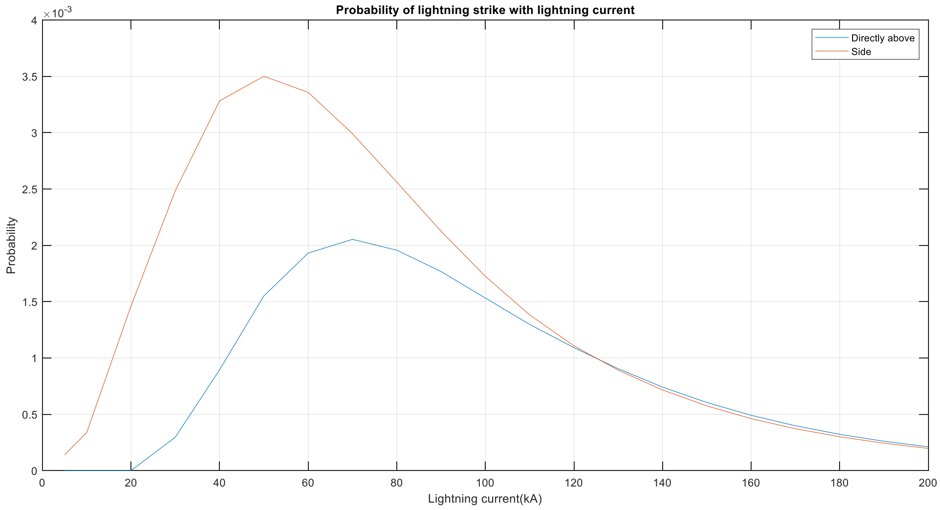


Figure 7. 5 Probability of lightning strike to Jethawanaya stupa at present dimensions

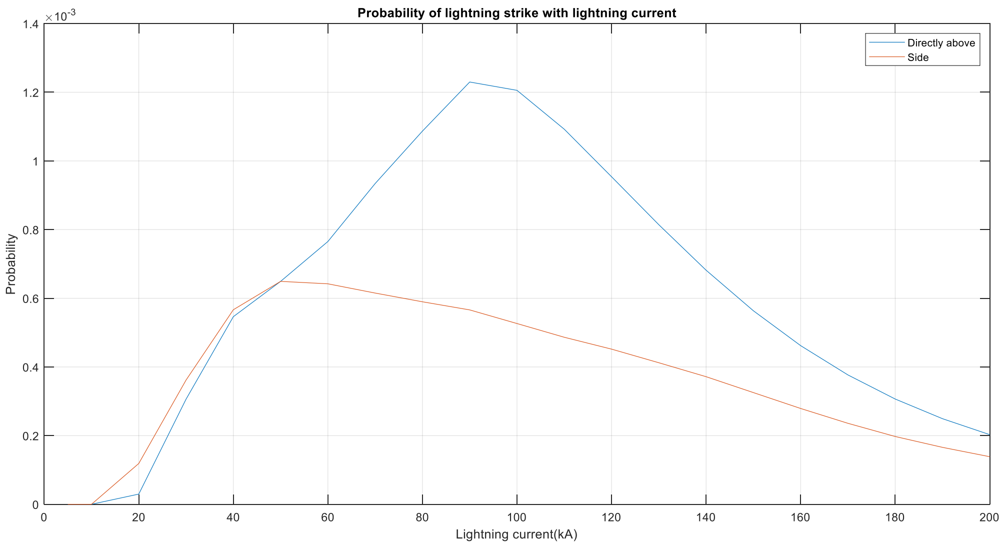


Figure 7. 6 Probability of lightning strike to Mirisawetiya stupa at present dimensions

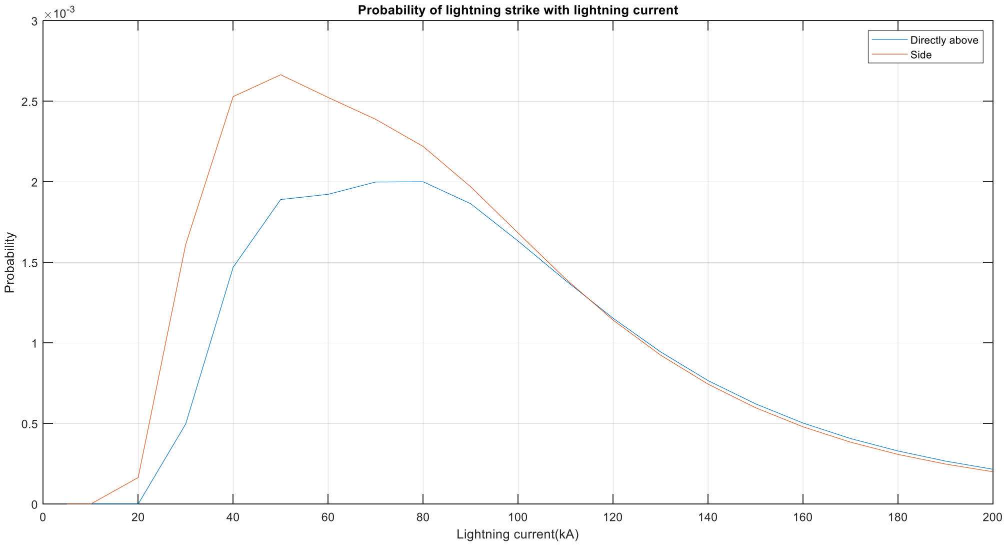


Figure 7. 7 Probability of lightning strike to Ruwanwaliseya stupa at ancient dimensions

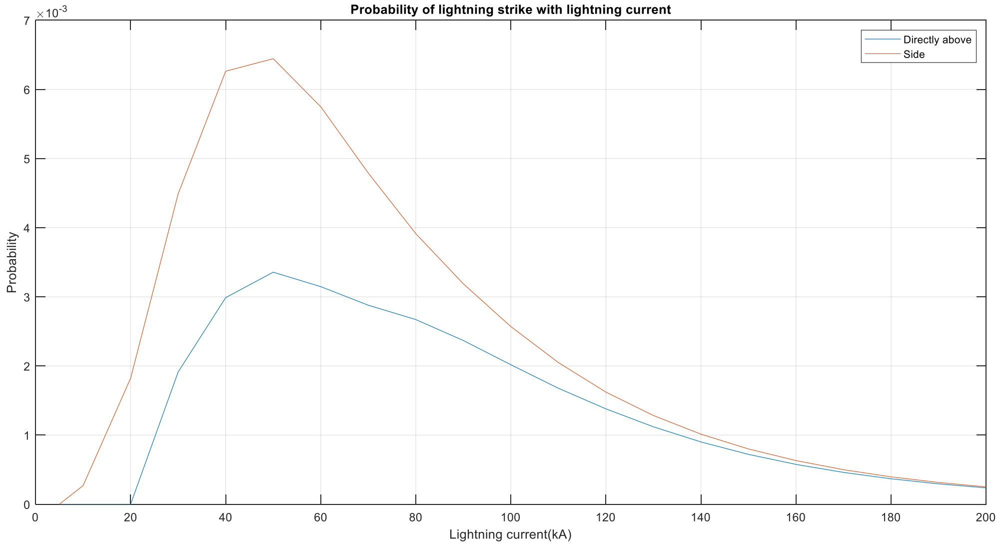


Figure 7. 8 Probability of lightning strike to Abayagiriya stupa at ancient dimensions

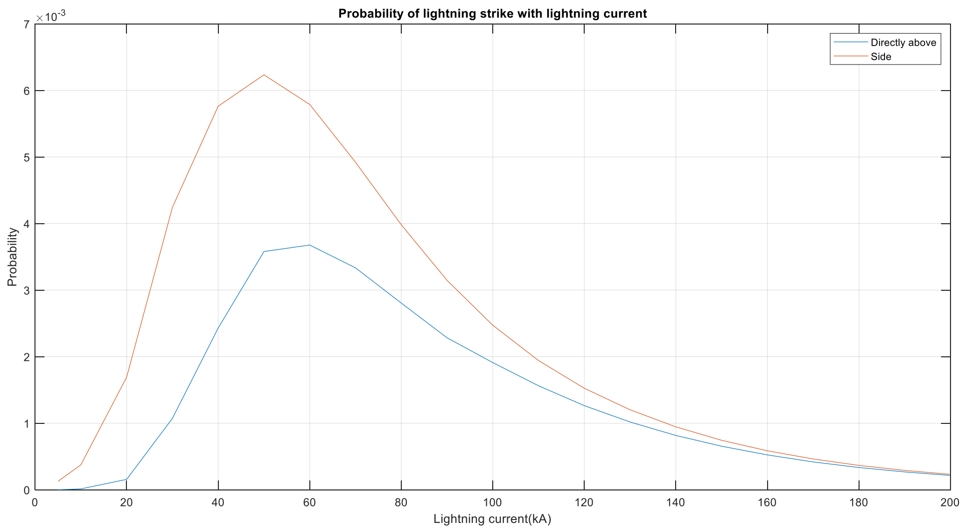


Figure 7. 9 Probability of lightning strike to Jethawanaya stupa at ancient dimensions

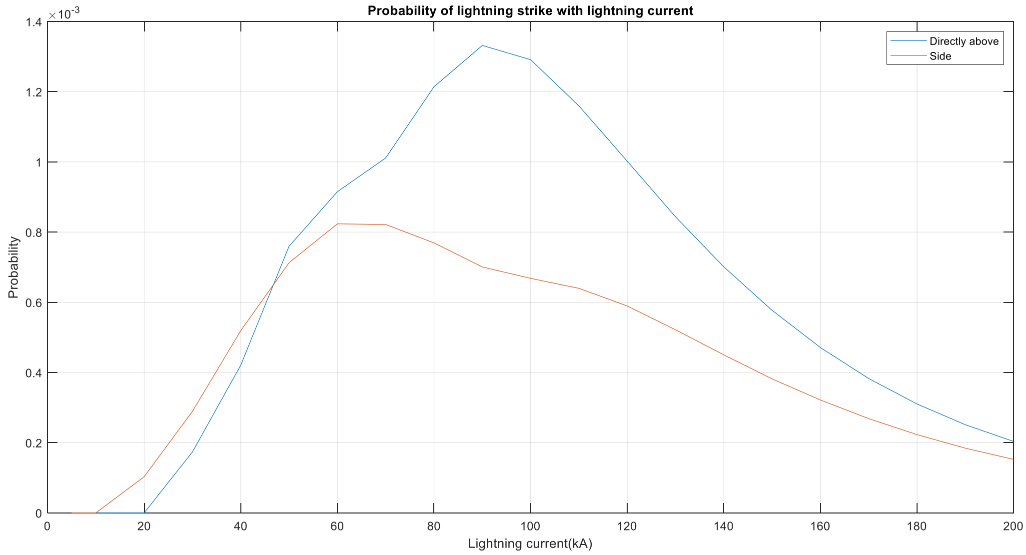


Figure 7. 10 Probability of lightning strike to Mirisawetiya stupa at ancient dimensions

Probability of lightning damage to the structures by using the results from geometrical analysis

For the calculation of probability of lightning strike, the unprotected area obtained by the results from the rolling sphere method was used. For this case 30kA lightning was considered.

$$\boldsymbol{Probability\ of\ lightning\ damage = Probability\ of\ lightning\ initiation} \times \frac{\boldsymbol{Unprotected\ area\ of\ stupa}}{\boldsymbol{Total\ area\ of\ stupa}}$$

Table 7. 1 Probability of lightning damage to stupa structures by using geometrical analysis results

Condition	Stupa	Stupa area	Unprotected area (mm^2)	$\frac{\text{Unprotected area}}{\text{Stupa area}}$	Probability of lightning damage
Present	Ruwanveliseya	30361996011.040	150017631.650	0.004941	6.028×10^{-5}
	Abayagiriya	17057109568	1687196013.390	0.098915	1.206×10^{-3}
	Mirisavetiya	5814746681.250	0	0	0
	Jethawanaya	17096848044.240	1204197098.150	0.070434	8.593×10^{-4}
Ancient	Ruwanveliseya	17886791069.070	271127145.100	0.015158	1.849×10^{-4}
	Abayagiriya	24287917627.560	962099712.3	0.039612	4.832×10^{-4}
	Mirisavetiya	6544794232.530	0	0	0
	Jethawanaya	25323164249.770	1419122259.120	0.05604	6.837×10^{-4}

CHAPTER 8
PROBLEMS ENCOUNTERED

- Finding the exact specifications of the stupa structures
- Modeling of the Citadel of the king Vijayabahu I
- Difficulty of finding correct tools in COMSOL software
- Creating mesh of structures using COMSOL software
- SOLIDWORKS modeling of Unprotected Zones

CHAPTER 8 CONCLUSIONS

With the analysis of the 3D models, we have concluded that the present stupa structures consist of the unprotected regions from both the geometric based analysis and the electrostatic field distribution.

According to the results obtained for the present stupa structures with LPS,

- Ruwanweliseya has risk of lightning attacks to square chamber for 30kA side strike case and for 200kA worst case scenario from both directly above and side.
- Abayagiriya also has some risk but electric field on the top of the stupa is higher, the risk is not significant.
- Jethawanaramaya and Mirisawetiya has no risk.

Furthermore, for the each of the stupa structures, we have provided with the recommendations on applying of copper flat strips along the unprotected region to avoid structural damages to the stupa structure. We have also analyzed the Ancient stupa structures, which yielded similar results. And it concluded that the structures are vulnerable in some regions. The electric field distribution along the ancient stupas have also considered by using the geographical location of the stupas and the citadel of King Vijayabahu I. And it is concluded that the direct strike of the lightning towards the citadel is not protected by the stupa structures according to the analysis from the COMSOL Multiphysics software.

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APPENDIX

Lightning protection of a modern building was analyzed by using COMSOL Multiphysics.

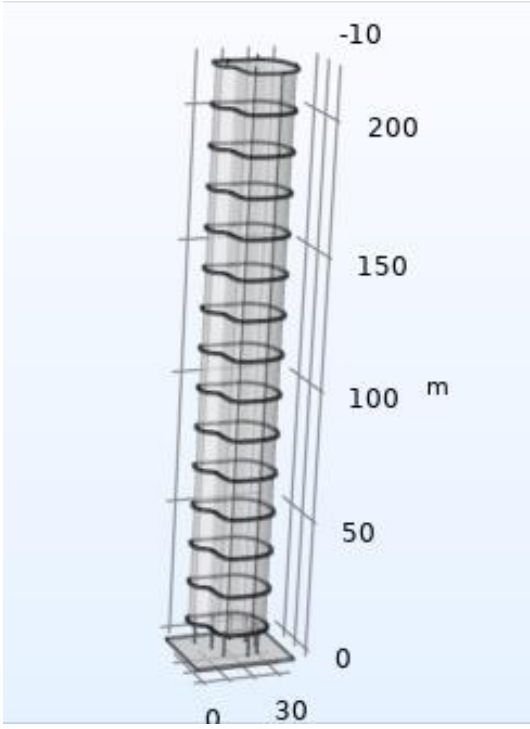

Figure: Building model in COMSOL

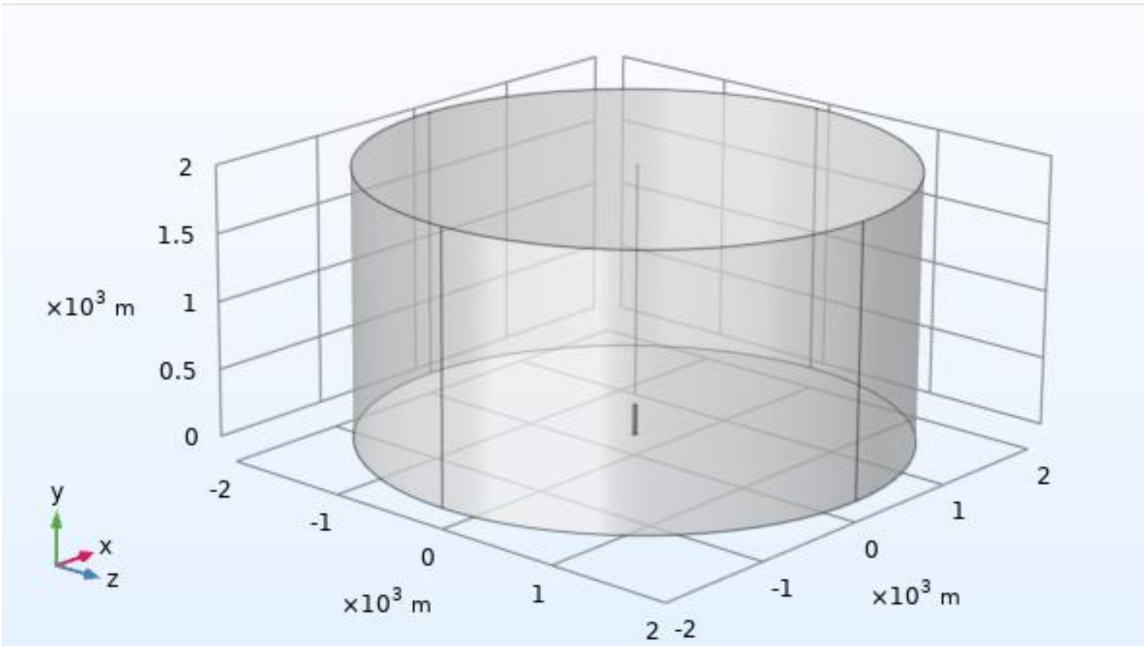

Figure: Total model of the system

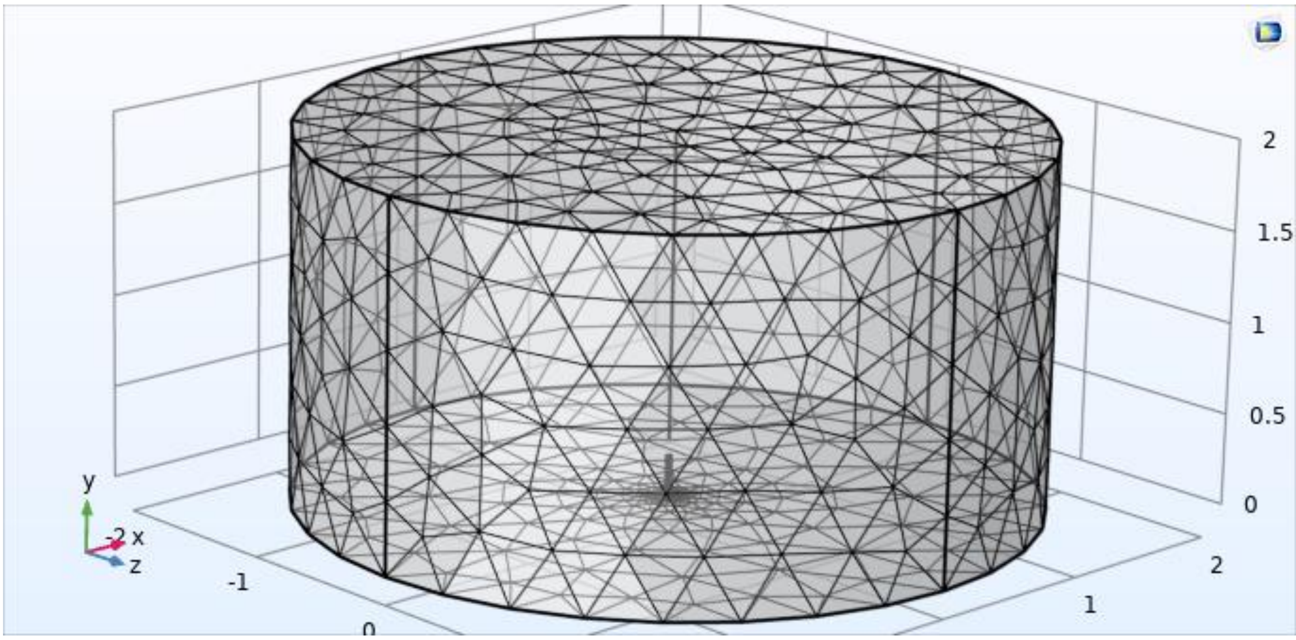

Figure: Mesh

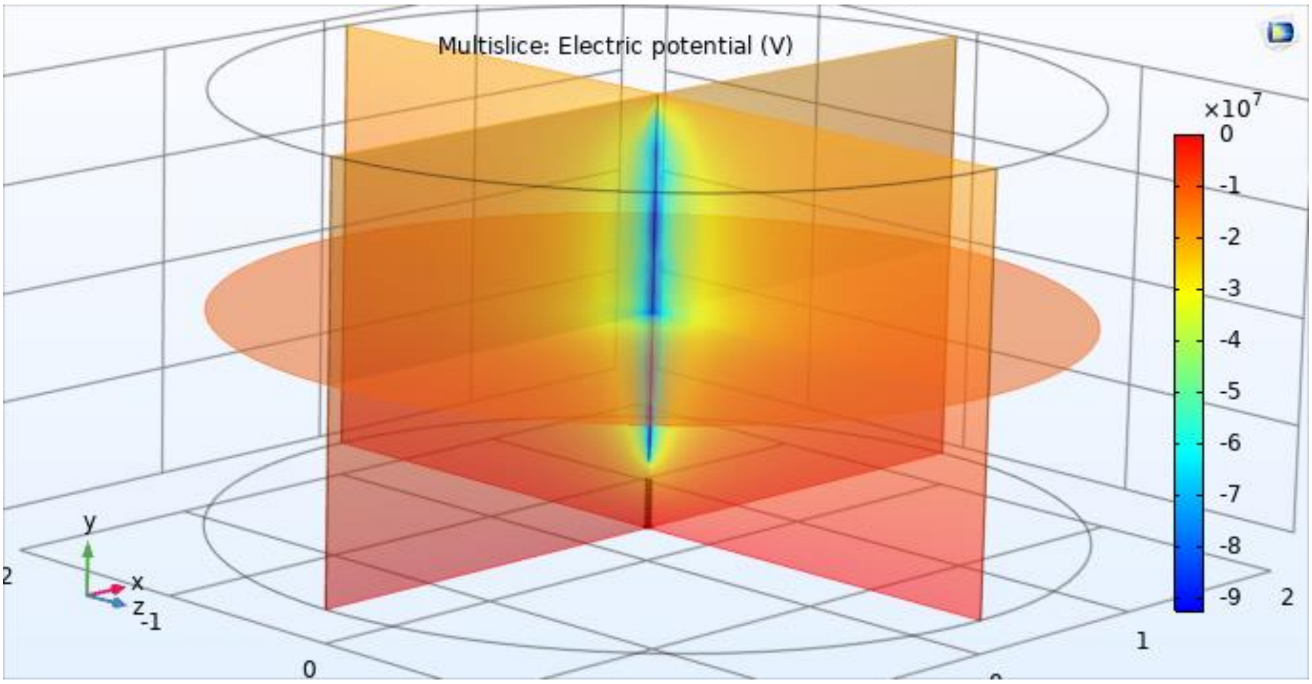

Figure: Electric potential

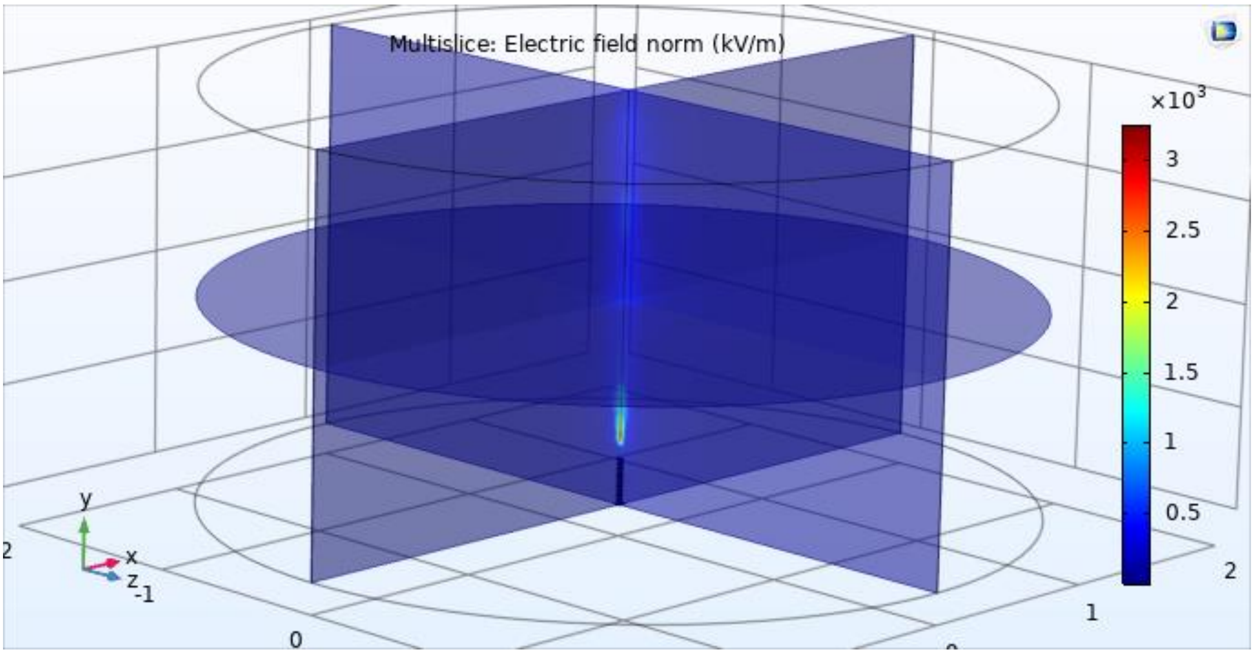

Figure: Electric field

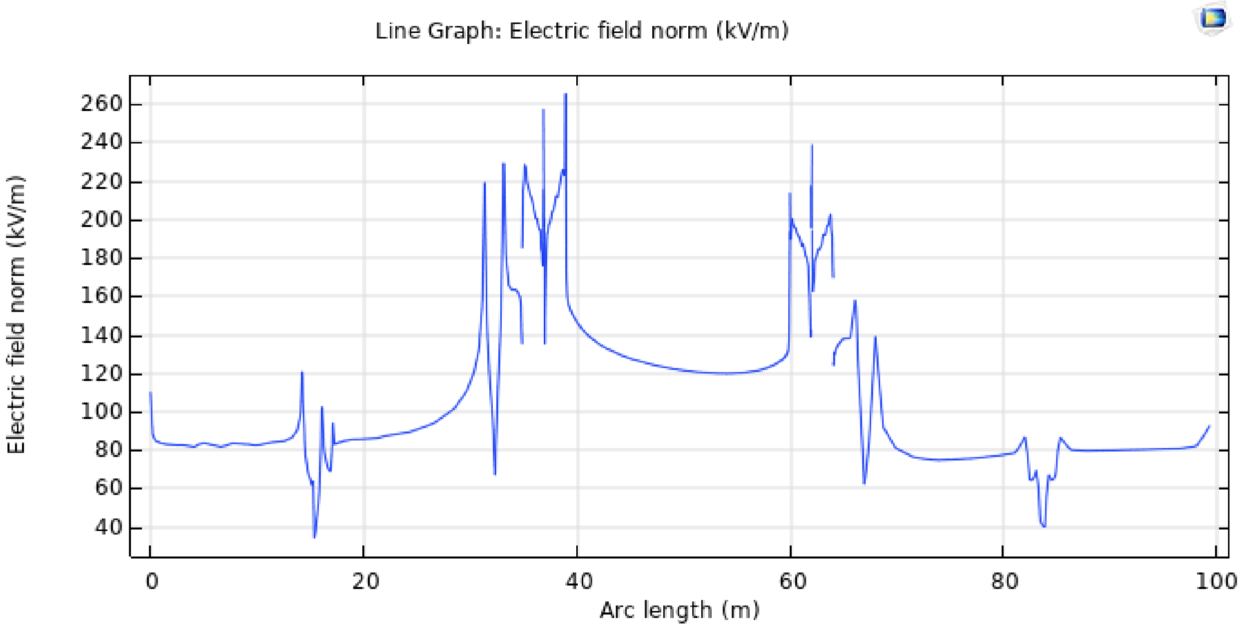

Figure: Electric field distribution along a line on the top surface of the building

According to above figure when a 30kA downward leader is closing directly above the building, air termination rods shows higher electric field compared to other parts of the building. Hence the building is protected against typical(30kA) lightning strike.