International Lightning Protection Association
1st Symposium

Valencia - Spain 24th-25th of November, 2011

ANGKOR VAT TEMPLE LIGHTNING PROTECTION

Sylvain Fauveaux Arnaud Lefort
INDELEC (France)

Abstract – The Temple of Angkor Vat is one of our precious Architectural and Cultural World Heritage. Being located in the Kingdom of Cambodia, this 12th century architectural complex suffered from lightning aggression. Shortly after the end of the local conflict, it was decided to protect this 8th Wonder of the World candidate. This challenging task had to cope with architectural and UNESCO constraints. A risk assessment being realized, an ESE lightning protection was proposed and installed in a proper way to avoid alterations of this stone made National Monument. A discussion about recent risk assessment method applied to this particular building is held.

1 - INTRODUCTION

Several years after the local conflict, this site has been listed as UNESCO World Heritage in 1992 owing to Japan and France's initiatives.

In 1995, a Cambodian Administrative Organization called *APSARA* is founded and begins the first actions of restoration of the temple and its statuary. One of the main concerns is then to protect the structure against a natural hazard : lightning, which caused recurrent damages to the top of the towers.

The challenge of such execution is twofold.

First, it is in question to analyze lightning hazards over the site and to design an effective lightning protection that is compatible with the architectural imperatives of this site. Then, these means of protection must be installed and commissioned, in a remote area where technical skills for that kind of installation are not very common.

At the end of the Lightning Risk Analysis, it appears that a lightning protection design at level I is needed. The E.S.E. Air Terminal lightning protection solution installed at the top of the towers, which is better suited, is retained and the accurate positioning of 5 air terminals allows a suited cover of the site. Such installation was done at the end of 1995.

2 - FACTS OF THE ANGKOR VAT COMPLEX

2 - 1 - Historical facts

Angkor Vat, located at a few kilometers from the city of Siem-Reap, is the most famous, most majestic temple of the capital city of Angkor of the Khmer Empire civilization founded by Jayavarman II (790-830). Angkor was confirmed to be a major place of the pre-industrial era. Its total area ranged over 3.000km² and its population was estimated up to 700.000 inhabitants.

Angkor Vat, which means "The City that is a Temple", is the hugest and best preserved monument of the Angkorian complex (*figure 1*). This temple, a funerary one, was erected by Sûryavarman II (1113-1145) before Cathedral Notre Dame of Paris. Its construction lasted 37 years. Angkor will be definitely abandoned as a capital city circa 1431, awaiting its resurrection.

Back at colonial times when Cambodia was about to be part of the French Empire as a Protectorate (1863), Angkor was rediscovered by Henri Mouhot (naturalist) in January 1860. After numerous expeditions, since the beginning of the 20th century, the site of Angkor was patiently renovated by, more particularly, the French School of Far East (E.F.E.O., *Ecole Française de l'Extrême Orient*) and Maurice Glaize [1].

These tremendous works led to retrieve Angkor from the Endangered World Heritage list of UNESCO in 2004 after 11 years of preservation tasks.

Figure 1 - Aerial view of Angkor Vat

On site works are supervised by a Cambodian Administrative Organization called A.P.S.A.R.A. (*Autorité pour la Protection du Site et l'Aménagement de la Région d'Angkor*, National Authority for the Protection of the Site and Development of the Region of Angkor).

2 - 2 - Architectural facts

The site sits on a plain, at about 20-30m above sea level. The main material used to build this site is sandstone and some laterite.
The outer wall, 1025 by 802 meters and 4.5 meters high, is surrounded by a 30-meter apron of open ground and a moat 190 meters wide (*figure 2*).
Access to the temple is by an earth bank to the east and a sandstone causeway to the west (main entrance).
The temple stands on a terrace raised above the level of the city. It consists essentially of three rectangular galleries rising to a central tower; with each level higher than the last one (*figure 3*).
The outer gallery measures 187 by 215 meters, with pavilions rather than towers at the corners. The second-level enclosure is 100 by 115 m. The inner gallery, a 60 meter square called *Bakan* ("Sanctuary"), is gathering the main structures, the latter being the tallest ones owing to its 5 towers. The tower above the central shrine rises 43 m to a height of 65 m above the ground, the central tower is raised above the surrounding four.
Elevation dimensions are given in *Table I*.
The ground of the area between by the inner wall and the second gallery is soil. The ground of the area inside the second and inner galleries is made of stone pavement as colorized in *figure 2* and *figure 9*.

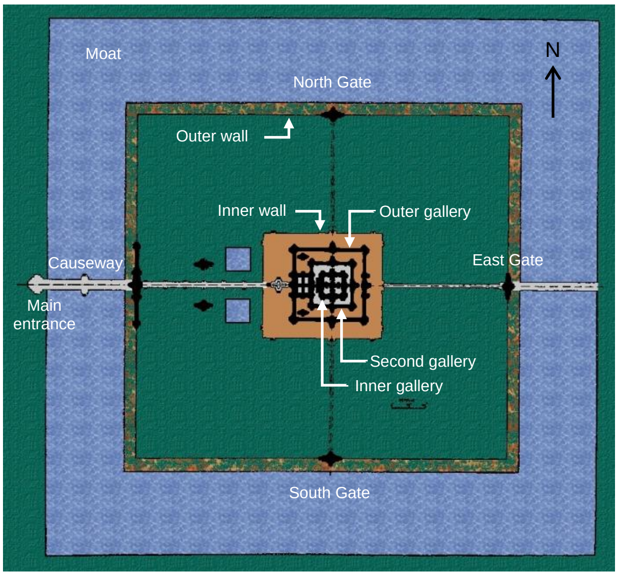


Figure 2 - General blueprint of Angkor Vat (scale is 100m)

Outer Gallery	
Corner pavilion	17.4
Side gates	18.8
Main Entrance pavilion	24
Libraries	18.5
Wall	13.5
Second Gallery	
Truncated Towers	30
Wall	18.8
Inner Gallery	
Central Tower	65
Towers	51
Wall	32

Table I – Elevation dimensions in meters

2 - 3 - The Temple and Lightning

As a result of partial destruction of the temple during a storm, UNESCO contacted directly the INDELEC Company to protect only the towers against direct lightning impacts. Indeed, tower tops are severely damaged by natural erosion and lightning through the years : some are truncated. Protecting the temple using the meshed cage method induced a large number of downconductors. Their installation and course along the structure quickly appeared to be non-compatible with the architectural essence of the temple. Indeed, the outer walls of the towers are exquisitely carved and composed of numerous projecting stone blocks (*figures 4, 5* and *6*). The downconductor courses are thus extremely delicate to implement. It's a challenge not to alter all these stonework and low-relief by drilling all the fixtures needed to attach downconductors. Moreover, bent radii must be observed according to the standards.

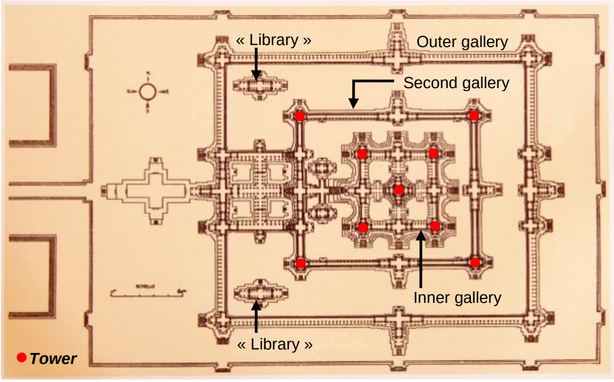


Figure 3 - Blueprint of Angkor Vat (scale is 50m)

Figure 4 - Upper part of the central tower of Angkor Vat

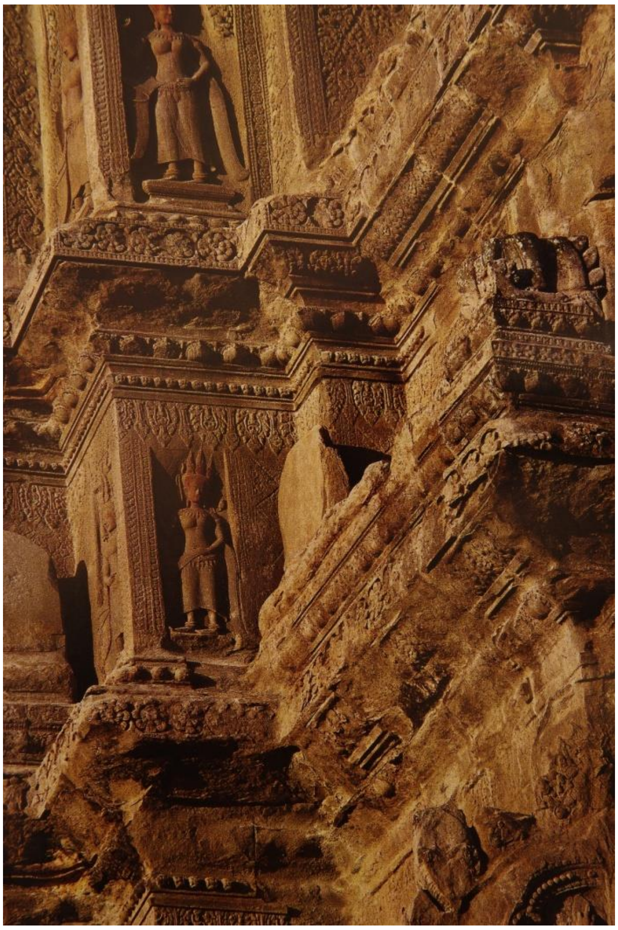


Figure 5 - Intricate carved walls

3 - RISK ASSESSMENT

3 - 1 - Local considerations

3 - 1 - 1 - Climate and lightning

The region is showing a hot and moist tropical climate. The heaviest rains, and also the lightning season, take place from May to October, peak temperatures are ranging from 27 to 35°C.
For a country that has an area 3 times smaller than France with its 14.7 million of inhabitants, lightning induced casualties are more than 10 times higher. In 2010, there were 114 dead people due to lightning and about 140 ones from January to mid August 2011. The keraunic level is 20 to 40 $km^{-2}.year^{-1}$, which is a huge number.

3 - 1 - 2 - Touristic frequenting

The touristic frequenting in Cambodia raised enormously : from 118.183 tourists in 1993 to 2.4 million in 2010 of whom almost 50% visit the temples of the Angkor area [2;3;4], see *figure 7*. In 2007 alone, income from tourists visiting Angkor Vat was approximately US$50 million [5].
Visits are open 7 days a week from 05AM to 06PM, that is 13 hours of daily presence for a minimal visit duration of 2 hours. In 2010, it represents in the mean 4307 persons daily and about 662 persons present on site during the same 2 hour visit.

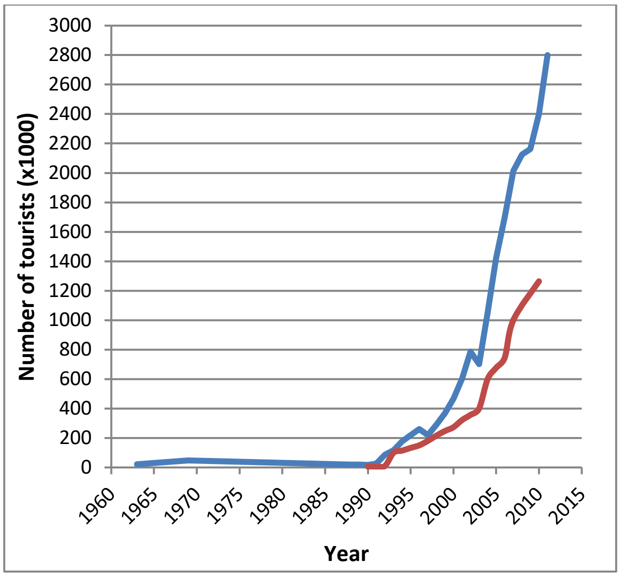


Figure 7 - Evolution of tourism in Cambodia (upper blue trace) and in Angkor Vat (lower red trace)

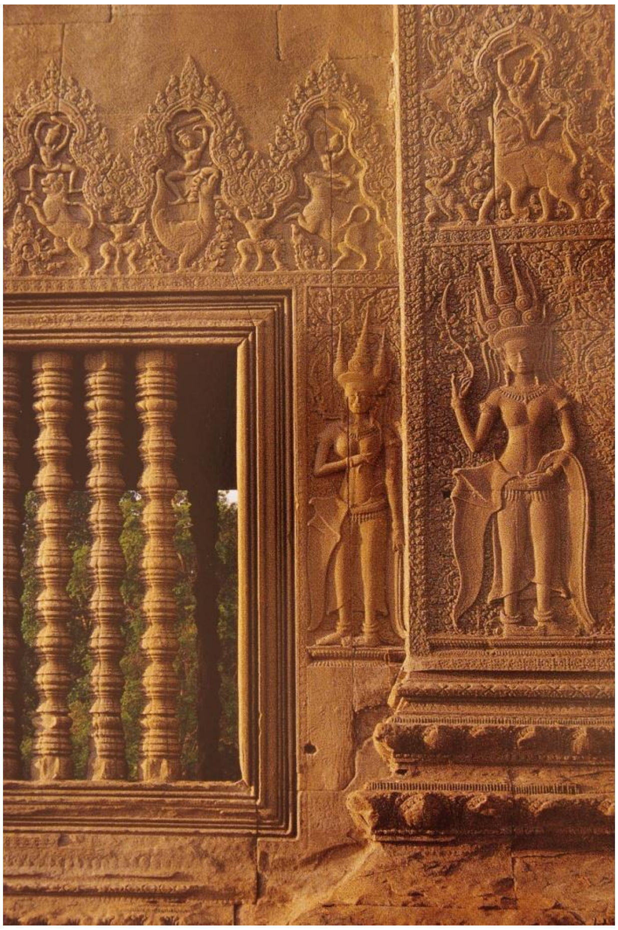


Figure 6 - Delicate ornamented walls

3 - 1 - 3 - Electrical environment

There are no electric lines except a small lighting network strictly limited to the causeway leading to the temple and to the low-relief North gallery. In the following analysis, these electric lines are then omitted.

This limitation was decided by the Authorities to avoid drilling alterations of the temple because of the fixing of the lighting. Moreover, visits take place during the daylight period, so the added artificial light was not necessary and not welcome.

3 - 2 - Collection area for flashes

Whatever Lightning Risk Analysis used, the equivalent collection area for flashes must be calculated. It is a function of the size and height of the building. As the complex is large and tall with many different heights, the determination of the equivalent area is not direct. The calculation is based upon graphical method owing to *Table I*.
The collection area of the whole temple (delimited by the 3 galleries) is by far dominated by the central tower (*figure 8*). It was calculated according to lightning standards [6;7;8]. The total area is equal to about 123,517m² (0.123km²).

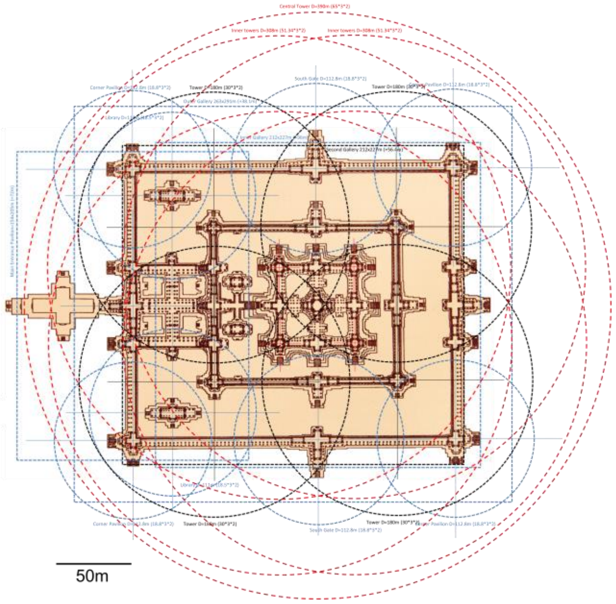


Figure 8 – Collection Area for Flashes of the Temple

3 - 3 - NFC 17102 (1995) [6]

The Risk Analysis, done in 1995 according to Annex B of the NFC17102 standard [6] before the installation of the lightning protection, did take into account the parameters of that time only, namely the goods, in this case towers that represents the highest spots of the temple likely to be struck by lightning. At that time, the touristic frequenting was 132,700 people, that is about 56 persons present on site during the same 2 hour visit. The site occupancy was considered as « normal » and the risk of panic weak not to say inexistent. In 2010, the number of people on site at the same time increased more than tenfold (662).

<u>Parameters used are :</u>
N_g = 30 km^{-2}.year^{-1}
A_e = 123,517m²
C_1 = 0.5 Structure surrounded by smaller structures
C_2 = 1 Usual structure, common roofing (materials)
C_3 = 3 Exceptional value, irreplaceable
C_4 = 1 Structure showing normal occupancy
C_5 = 1 No need of uninterrupted service or consequence to the environment

The calculation leads to :
N_d = 3.70551
N_c = 1.833.10^{-3}

$N_d > N_c$ then a lightning protection is mandatory.

The effectiveness of the protection to be installed is calculated and equal to E = 0.99950. This value of E matches a protection Level I with added measures.

3 - 4 - UTE C 17108 (2006) [7]

This Lightning Risk Analysis details the main components that are Risk R_1 (Loss of human life), Risk R_2 (Loss of public service) and Risk R_3 (Loss of cultural heritage).
This method of analysis was published in 2006 and thus was not implemented when the project was decided.

<u>Keeping the same parameters of the installation (1995) :</u>
N_g = 30 km^{-2}.year^{-1}
A_d = 123,517m²
C_d = 0.5 Structure surrounded by smaller structures or same height
h = 2 Weak level of panic (<100 people)
r_f = 0.001 Weak level of fire hazard (minimum value of this parameter)
L_{f1} = 0.1 Structure showing normal occupancy
L_{f2} = 0 No service
L_{f3} = 0.1
No lightning rod.
No SPD (Surge Protection Device).
No electric line.

Results are :
R_1 = **3.71.10^{-4}** (>Tolerable Risk R_{T1}<10^{-5})
R_2 = 0
R_3 = 1.85.10^{-4} (<R_{T3} < 10^{-3})

One can note that only Risk R_1 (Loss of human life) leads to a necessary protection. That is to say that the Loss of irreplaceable cultural heritage R_3 is not evidential although it was the main concern in 1995 !
In order to satisfy to the criteria R_1, a Level I protection is mandatory.

<u>Applying today's parameters (2010) :</u>
h = 5 Moderate level of panic (<1000 people)

Results are :
R_1 = **9.27.10^{-4}** (>Tolerable Risk R_{T1}<10^{-5})
R_2 = 0
R_3 = 1.85.10^{-4} (<R_{T3} < 10^{-3})

By using these updated parameters and this method of Lightning Risk Analysis, it is not possible to efficiently protect against Loss of human life whereas Loss of cultural heritage is never evidential.

3 - 5 – IEC/EN 62305-2 (2006) [8]

In order to better understand the action of the different parameters on the method of Lightning Risk Analysis, we chose to implement the one from the International and European standard IEC/EN 62305-2.

First, we will care about Risk R_3, result of the Cambodian Administration's concern. Therefore, we will deal with Risk R_1.

Keeping the same parameters of the installation (1995) :
N_g = 30 km^{-2}.year^{-1}
A_d = 123,517m²
C_d = 0.5 Structure surrounded by smaller structures or same height
P_B = 1 Structure non protected by any LPS
L_T = 10^{-2} "Typical" structure (people inside the buildings)
L_{f1} = 2.10^{-2} Museum type of structure
$r_p = 1$ No measure against fire hazard
r_f = 0 No fire hazard (minimum value of this parameter)
h_z = 2 Weak level of panic (<100 people)
L_{f3} = 0.1
Presence of 56 people during 4745 hours/year.
No service.
No SPD.
No electric line.

Risk R_3 depends on :

- The equivalent collection area,
- The LPS,
- The measures against fire hazard,
- The sensitivity to fire.

Results are :
R_1 = 0
R_3 = 0

The structure being constructed with non inflammable stone blocks, there is no fire hazard (minimum value of this parameter) and thus Risk R_3 is equal to 0.

We observe that Risk R_1 (Loss of human life) do not lead to the necessity of protection contrary to the method used in paragraph 3-4-. Though, fall of stone block pieces can occur because of direct strike.

If we modify the analysis by stating that it is a structure with people outside the buildings, as a consequence Risk R_1 is equal to 1.01.10^{-5}, and the Loss of cultural heritage is no more managed (Jupiter software). A simple warning or physical restriction is sufficient to release the danger according to the analysis. If the number of people present on site skips to 663 people during the same 4745 hour duration (annual total), the value of Risk R_1 is unchanged while on site occupancy has increased more than tenfold.

3 - 6 - Discussion

Dealing with such archeological site, by using 3 methods of Lightning Risk Analysis, results are rather illogical.
With the first method, a bit primitive looking after the release of the two last ones in 2006, indeed, it is not possible to separate the mains components like Loss of human life or Loss of cultural heritage.
Despite the relative modernity of the 2 last methods, we note that Risk R_3, concern which we are mainly interested in (cultural heritage), is systematically underestimated if not ignored and does not need any protection. However, the towers of the building did catch lightning strokes and did suffer damages. Here it is the whole contradiction about this example of archeological site.
This site is entirely made of stone (sandstone and some laterite), thus there is no inflammable material.

Calculating R_3 (IEC/EN 62305-2), we observe that parameter r_f about fire hazard is directly factorized (1) (2) (3) with all other parameters (without indoor electric line). As materials are not inflammable, so this parameter r_f is equal to 0 and Risk R_3 cancels out !

$$R_3 = R_B = N_D . P_B . L_B \qquad (1)$$
$$N_D = N_g . A_d . C_d . 10^{-6} \qquad (2)$$
$$L_B = r_p . h_z . \boldsymbol{r_f} . L_f \qquad (3)$$

An inconsistency arises : every building, without indoor electric line, bearing non inflammable materials (r_f=0) is « self-protected » speaking of Risk R_3 !! It is then the same case for numerous archeological sites.

Dealing with the UTE C 17108 standard, Risk R_3 is not null because the minimum value of parameter r_f about risk hazard is « weak fire hazard » (r_f = 10^{-3}). The following case r_f = 0 does not exist. However, the structure remains « self-protected », indeed Risk R_3 is below the tolerable risk value (R_{T3} < 10^{-3}).

How to « protect » the structure of an irreplaceable archeological site ? In other words, how is it possible for these both late standards to express the need of protection for that case ? Using these late standards, it is not achievable. This site, in the manner of an entirely stone made bell tower, is suffering damages ! In the future during any revision, it might be advisable to address such cases in the IEC/EN 62305-2 or UTE C 17108 standards.

Risk R_1 is taken into account but remains too high according to the UTE C 17108 standard. Which solutions can we implement in order to achieve a tolerable value ?
It is not possible to modify the archeological site without altering it in order to create safe zones (*shelters)* or multiple and faster fire exits.
An interesting solution might be the handling of Risk R_1 owing to proper forestalling implemented by a lightning storm warning system. Such system is now defined by a brand new standard [9]. Visitors should be evacuated and should take shelter in planned areas.
Speaking of the IEC/EN 62305-2 standard, Risk R_1 remains equal to 0 if people are inside the building. Outside the building, Risk R_1 is on par with the tolerable risk value so a simple warning sign is sufficient…

4 – INSTALLATION

The installation of the lightning protection took place in December 1995. Fitting of lightning rods and downconductors mobilized two qualified and well trained employees during 11 days as well as more than twenty local workers for burying tasks of earthing systems.

In order to protect any towers and cover the area of the temple, 5 Early Streamer Emission Air Terminals (ESEAT) were implemented (*figure 9*) at the top of 2 meter poles to limit the visual annoyance. These 5 ESEATs were manufactured and supplied by the INDELEC Company, Top Set 4 model, 50µs advance time each. This model was preferred because of its low profile and unobtrusive silhouette. Its protection radius is 68m at Level of Protection I according to the standard [6]. The protection zone perfectly covers any tower, as specified by the technical requirement specifications, as well as public areas, namely the surface delimited by the 3 galleries. The architectural structures and people are thus protected at Level I.

Downconductors are solid 8mm diameter round copper wires according to the standards [6 ;10 ;11]. One downconductor for each ESEAT, according to the installation standard in force at that time [6], attached by 3 fasteners every meter and distributed at best depending on the availability of non carved surfaces of the stone walls.

Paths of the downconductors are running along the towers and galleries in order to blend in with the stone material. It was a bit of a challenge to satisfy the 3 fixture per meter rule, the bent radii (*figure 10*) and the architectural constraints (stone works).

No protection sheath was implemented with the sole intention of low visual annoyance, being said that no vehicle or motorized equipment is moving about the downconductors.

Furthermore, the earthing system network is designed to insure the lightning current spread out inside the temple area owing to free ground access (soil). Earthing systems are triangle ones, made of standard tined copper tape and standard vertical electrodes (copper electroplated steel). Each earthing system was interconnected to each other to take advantage of the added length of buried of electrical conductors, every earthing system is showing a resistance value lower than 10 Ω according to the standard [6].

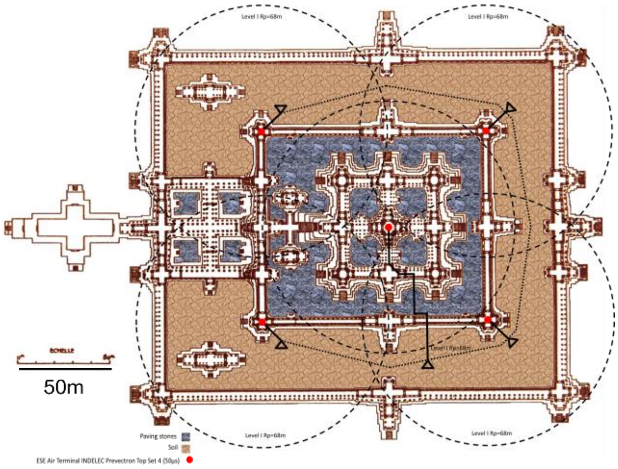
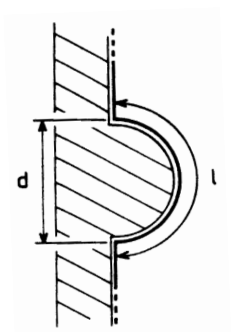


Figure 9 – ELPS of the temple and zone of protection



$$d > \frac{l}{20}$$

Figure 10 – Downconductor bend condition

5 - INSPECTION

The last inspection was conducted in January 2009 according to the NFC17102 standard. Everything was OK (visual examination, earth termination measurement, etc…), except one downconductor which its lowest part was partially unclipped. This site is rather simple to verify because there is no metallic items or electrical lines and no building extension was added to the temple. So there is nothing special to discuss about this topic.

6 - CONCLUSION

This Angkor Vat temple, which one had to suffer from lightning aggressions all the way through centuries, is from now on protected for about fifteen years. The least invasive accepted solution was the one using ESEATs. Five of them were implemented with their own respective downconductor that was attached to the structure with the upmost respect of the multi century testimonial from its intricate carved walls.

Dealing with the latest methods of Lightning Risk Analysis, we observe a relative discrepancy about this kind of open air archeological site made of non flammable materials but fragile ones when faced to lightning aggression.

No more damages to the temple due to lightning were to be deplored since the installation of the lightning protection system. However, the temple has to face another threat : degradations induced by mass tourism [12].

7 - REFERENCES

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Figures 4-6 : Courtesy of Suzanne Held.

Corresponding author

Name: Sylvain Fauveaux

Address: INDELEC 61 Chemin des Postes 59500 Douai - FRANCE

Fax: +33 3 27 944 945 ; Phone: +33 3 27 944 293

E-mail: sfauveaux@indelec.com