



Simulation of Two Basic Connection Scenarios during Attachment Process based on a Stochastic Lightning Leader Model

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Abstract—The development of most upward positive leaders does not branch during the downward negative cloud-to-ground lightning strikes; therefore, we modified the simulation scheme of the upward positive leader based on a two-dimensional stochastic lightning leader model so that the upward leader does not branch during its development. By using the modified model, we simulated two basic connection scenarios, i.e., the "tip-to-tip" and the "tip-to-lateral", of the leader connecting behavior between the downward negative leader and the upward connecting positive leader during the attachment process in tall-object lightning flashes.

Keywords: tall-object lightning; attachment process; junction point; tip-to-lateral; simulation

I. INTRODUCTION

The lightning attachment process is one of the least understood lightning processes. Understanding of the lightning attachment process is vital for improving lightning protection techniques [e.g., 1-3].

When the downward leader and upward leader approach one another, it is generally thought that the tip of the downward leader (DL, usually negative) will connect to the tip of the upward connecting leader (UCL, usually positive), i.e., "tip-to-tip" connection. However, new findings have recently emerged. In the high-speed video image data analysis of one downward negative cloud-to-ground (CG) flash striking the 440 m high Guangzhou International Finance Center (GIFC), Lu et al. identified for the first time the phenomenon that the connection of the DL's tip to the lateral surface of the UCL, i.e., "tip-to-lateral" connection [4]. Gao et al. also noted a similar situation in another lightning flash [5]. Further analysis indicates that during the attachment process in which lightning strikes tall structures, the "tip-to-lateral" connection is more common than "tip-to-tip" connection [6].

In this paper, we modified a two-dimensional (2-D) stochastic lightning leader model to simulate and analyze the attachment process in tall-object lightning flash. By altering the

horizontal distance from the initiation location of the DL to the tall structure, we derived the probability of grounding point at different location, the occurring probability of "tip-to-lateral" connection, and the ratio of the part of the UCL above the junction point that accounts for the entire length of the UCL upon the "tip-to-lateral" connection.

II. MODEL DESCRIPTION AND EXPERIMENTAL DESIGN

A. Model description

In [7], Ren et al. established and validated a 2-D stochastic lightning leader model, and the simulation indicates that the development of the negative DL is subject to the obvious branching phenomenon; moreover, the branching is more obvious when it propagates closer to the ground, which is consistent with actual observations. However, the simulation result of the upward positive leader (UPL) induced by the DL in [7] also often exhibits multiple branches.

According to the field experiment observation, although most of the UPLs in upward lightning flashes have multiple branches, the phenomenon of a branching UPL induced by the DL in downward negative CG flash is not common. So we modified the simulation scheme of the UPL in the stochastic model.

As shown in Fig. 1, the DL (negative) and the UPL differ when determining the next point of development. When we determined the next point of development for the DL, we first calculated the electric field for all of the adjacent points of every developed point of the DL (the upper part of Fig. 1). The solid circles represent the developed points of the DL, and the open circles represent the adjacent grid points of the DL. Then we selected the points that satisfied the electric field condition for the leader propagation (indicated by the open circles with the relatively thick line in the figure) as the next possible points to be developed. Finally, we calculated the probability of every point being developed using equation $P_i = |E_i - E_{th}| / \sum_i |E_i - E_{th}|$, $|E_i| > |E_{th}|$ (E_i is the electric field at each point to be developed, and E_{th} is the threshold of the electric field for leader

propagation); the probability of all the points being developed constitutes a probability range of (0, 1]. The next point of development was determined through the random number generated by a stochastic function. For the UPL, only the grid point in the adjacent of the previous point of development is likely to become the next point of development, as shown by the open triangles in Fig. 1 (the solid triangle is the existing point of development for the UPL). Similarly, we first selected the point to be developed according to the calculated electric field (the open triangles with the thick line in Fig. 1) and then determined the next point of development for the UPL according to the probabilities.

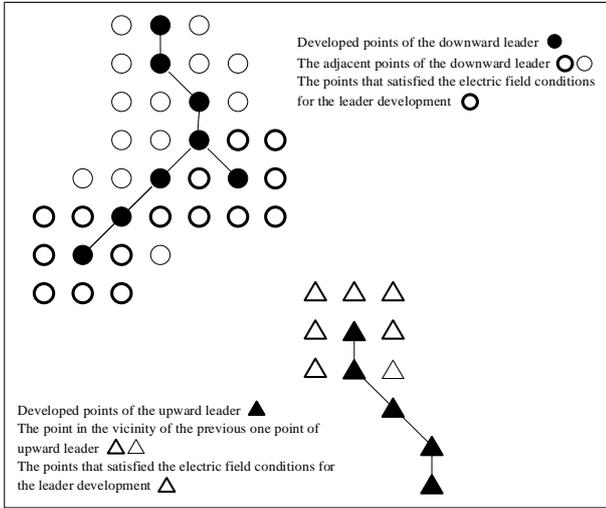


Figure 1. Schematic diagram for the development of the downward and upward leaders

The simulation region is 1200×1000 m near the ground surface. The electrical potential of the ground surface and tall structure is 0 V. The downward leader initiates from a height of $y=1,000$ m, and the potential for the downward negative stepped leader is -40 MV. The height of the tall structure on the ground is set to 440 m (which is the height of the GIFC); the central location of the tall structure is 800 m in the horizontal direction on the ground, and its width is 60 m. The upper boundary of the air, the downward leader, the tall structure on the ground, and the ground surface all satisfy Dirichlet boundary condition and the lateral boundary for air satisfies the Neumann boundary condition. The spatial potential in the simulation region also satisfies Poisson's equation. By solving Poisson's equation, we derived the potential of each point in the simulation region and further derived the electric field to determine the next point of development of the leader. The ratio between the velocity of the DL and the UPL was 4:1. The electric field thresholds for the positive and negative leader propagation and for the initiation of the positive leader were simply assumed to be 216 kV/m [8]. The threshold for connection was 500 kV/m [9].

B. Experimental design

The spatial resolution in the simulation region was set to 10×10 m, and the rules of the attachment process on the tall structure were analyzed by altering the horizontal distance (d)

from the initiation point of the DL to the tall structure. As shown in Fig. 2, the tall structure was located 800 m above the ground. Beginning from the point directly above the center of the structure, every interval of 100 m to the left was set as one cause of study, i.e., $d = 0, 100, 200, \dots$, and 700 m. For each case, the simulation was run 400 times. Our focus was to derive the statistics on the location of grounding points and the location of junction points.

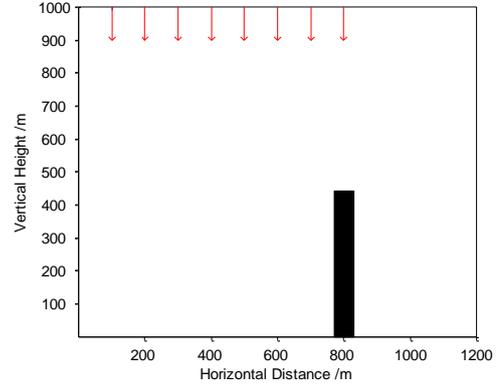


Figure 2. The tall structure and the selection of initiation positions for the downward leader

III. SIMULATION RESULTS AND ANALYSIS

A. The location of grounding point

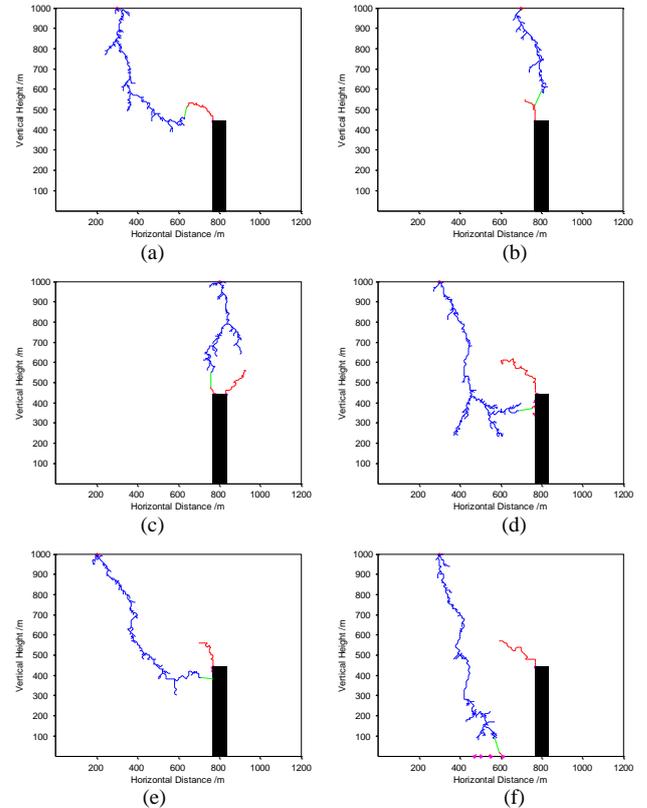


Figure 3. Different locations of the grounding point

Fig. 3 shows different locations of the grounding point. Fig. 3(a), (b), and (c) show the situation in which the grounding point is on the top of the tall structure: in (a), the DL connects to the UCL with “tip-to-tip” behavior; in (b), “tip-to-lateral”; in (c), there are several upward leaders from the top of the tall structure, and the DL connects to one of them. Fig. 3(d) and (e) show the situations in which the grounding point is on the side of the tall structure: in (d), the DL connects to the tip of the UCL; additionally, there are several upward unconnected leaders on the side and top of the tall structure; in (e), the DL connects directly to the side of the tall structure, and an upward unconnected leader is also present. Fig. 3(f) shows the situation in which the grounding point is on the ground.

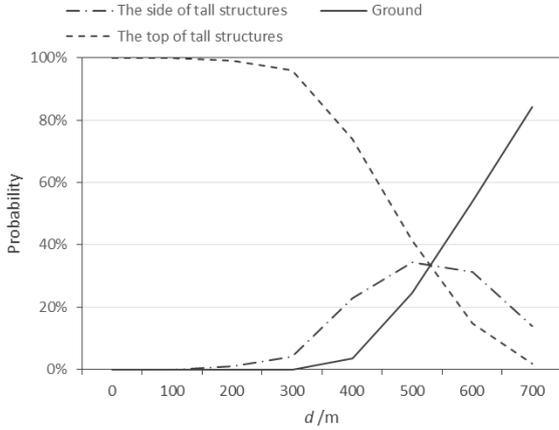


Figure 4. The variation trend of grounding probability at different locations with the value of d

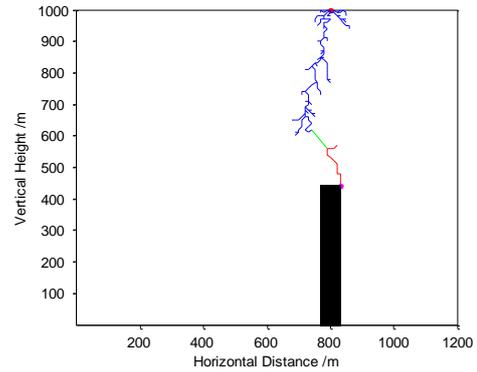
The variation trend of grounding probability at different locations with the value of d is shown in Fig. 4. It can be seen that the probability for the top of the tall structure to be struck by lightning decreases as the value of d increases. When $d \leq 300$ m, the probability for the grounding point to be located on the top of the tall structure is higher than 96%. When $d \geq 200$ m, it is possible that the side of the tall structure will be struck by lightning; the probability reaches its maximum when $d=500$ m and then begins to decrease. When $d \geq 400$ m, there is a high probability that the ground surface will be struck by lightning, and the probability obviously increases as d increases. Generally, when d is approximately 500 m, the probability of grounding point at the three different locations is comparable.

B. “tip-to-lateral” connection

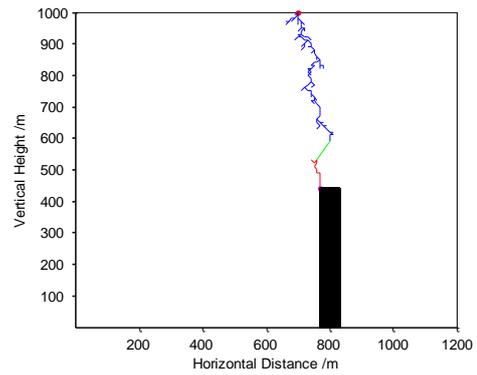
Most of the “tip-to-lateral” connection occurs between the DL and the UCL initiated from the top of the structure, so only the UCL from the top of the structure is analyzed in this section. Fig. 5 shows some examples of the simulation results of the “tip-to-lateral” connecting behavior with different values of d .

Fig. 6 presents the probability trend for the “tip-to-lateral” connection and the variation trend of the ratio between the length of the UCL above the junction point and the total length of the UCL (R) with the value of d . It can be seen that as d increases, the probability of the “tip-to-lateral” connection generally exhibits a trend of first increasing and then

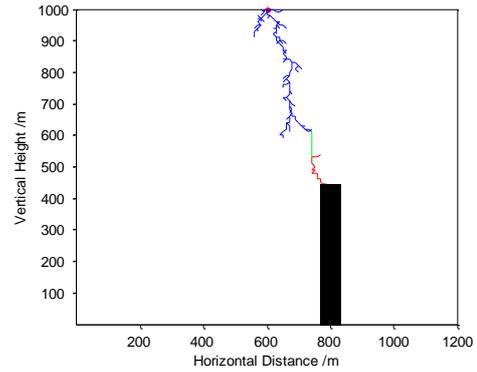
decreasing, reaching its maximum of 58% when $d=500$ m. This result indicates that when $d \leq 500$ m, the DL is prone to strike the lateral surface of the UCL when the horizontal initiation location of the DL is farther from the tall structure. As d increases, the R generally exhibits an increasing trend.



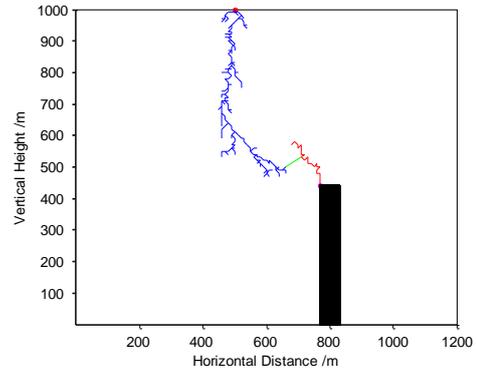
(a)



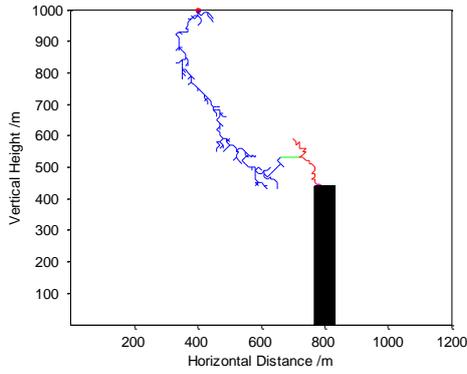
(b)



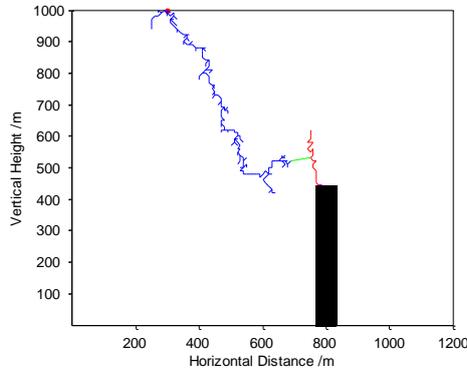
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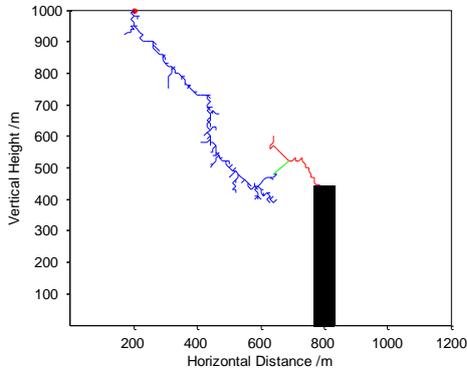
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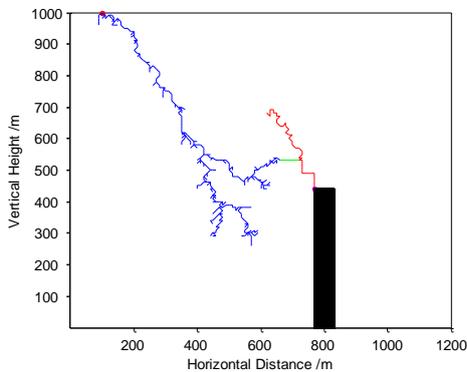
(e)



(f)

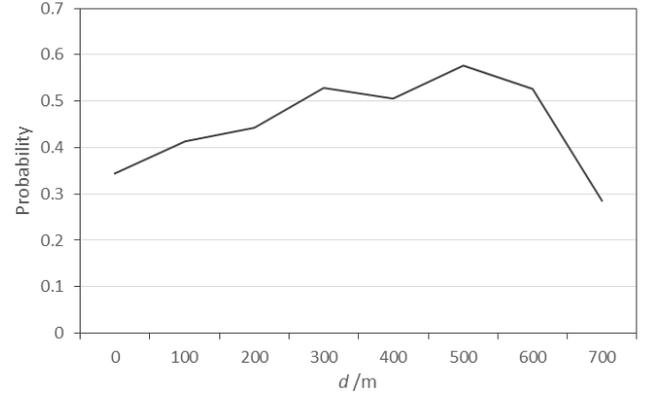


(g)

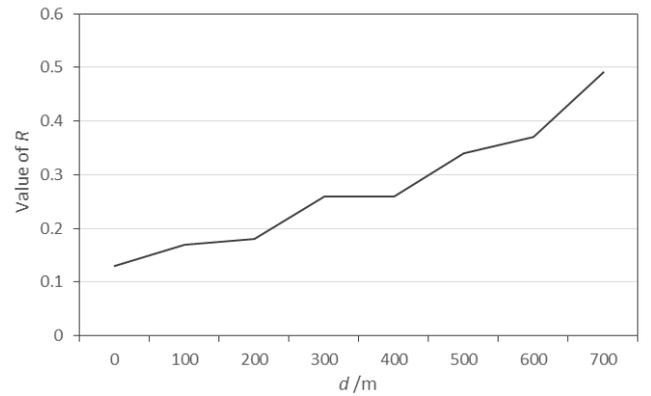


(h)

Figure 5. The examples of the simulation results of the “tip-to-lateral” connecting behavior with different values of d



(a)



(b)

Figure 6. Diagram of the probability trend for the “tip-to-lateral” connection (a) and the variation trend of the ratio between the length of the UCL above the junction point and the total length of the UCL (b) with the value of d

IV. CONCLUSIONS

By altering the horizontal distance (d) between the initiation point of the downward leader and the tall structure, we simulated the process of a tall structure (440-m high) being struck by lightning. We derived the statistics regarding the probability of grounding point at different location, the occurring probability of “tip-to-lateral” connection between the downward leader and the upward leader initiated from the top of the tall structure, and the ratio of the part of the UCL above the junction point that accounts for the entire length of the UCL upon the “tip-to-lateral” connection.

The probability of grounding at different positions is affected by the initiation position of the downward leader. When $d \leq 300$ m, over 96% of the grounding points occur on the top of tall structure; when $d > 300$ m, as the value of d increases, the probability for the grounding point to be located on the top of tall structure rapidly decreases. The grounding probability on the side of tall structure firstly increases with d , reaches its maximum when $d = 500$ m and then begins to decline. The grounding point with a probability in excess of 50% is on the ground surface when $d > 600$ m.

The simulation results indicate that when the value of d increases from 0 to 700 m, the probability of a lateral strike for the UCL initiated from the top of the tall structure generally exhibits a trend of first increasing and then decreasing; it reaches a maximum of 58% when d is 500 m. And as the value of d increases, the ratio of the part of the UCL above the junction point accounting for the entire length of the UCL upon the “tip-to-lateral” connection generally exhibits an increasing trend.

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