SHIELDING OF OVERHEAD LINES

Striking Distance

Modern theory of shielding is based on the electrogeometric model (EGM) of lightning strike. The striking distance is the heart of EGM. Striking distance is defined as the distance across which the tip of a specific stepped leader will strike a grounded object. The striking distance will be influenced by the intensity of the electric field between the leader tip and the object to be struck. In turn, it will depend upon the charge density of the leader. Because the subsequent return-stroke current is proportional to the charge density of the preceding leader stroke, ultimately, the striking distance is a function of the return-stroke current. Whitehead and his colleagues proposed a simple relationship between the striking distance and the return-stroke current, as given in equation (4.19). An alternate equation, (4.20), has also been widely applied. These equations simply state that a stepped leader, which will eventually give rise to a return-stroke current of I_p kA, will strike any object from a distance of r_s meters. In other words, the stepped leader, during its descend to ground from the cloud, will strike any object which comes within reach of a hemisphere of radius, r_s, surrounding the leader tip. This is shown schematically in Fig. 1 where a descending stepped leader is seeking out a striking object within a radius of r_s, the striking distance corresponding to a prospective return-stroke current, I_p. Figure 2 shows that the stepped leader has found its 'victim' in a tall pole which happens to be within the leader's 'fang' which stretches out to a distance of r_s meters.

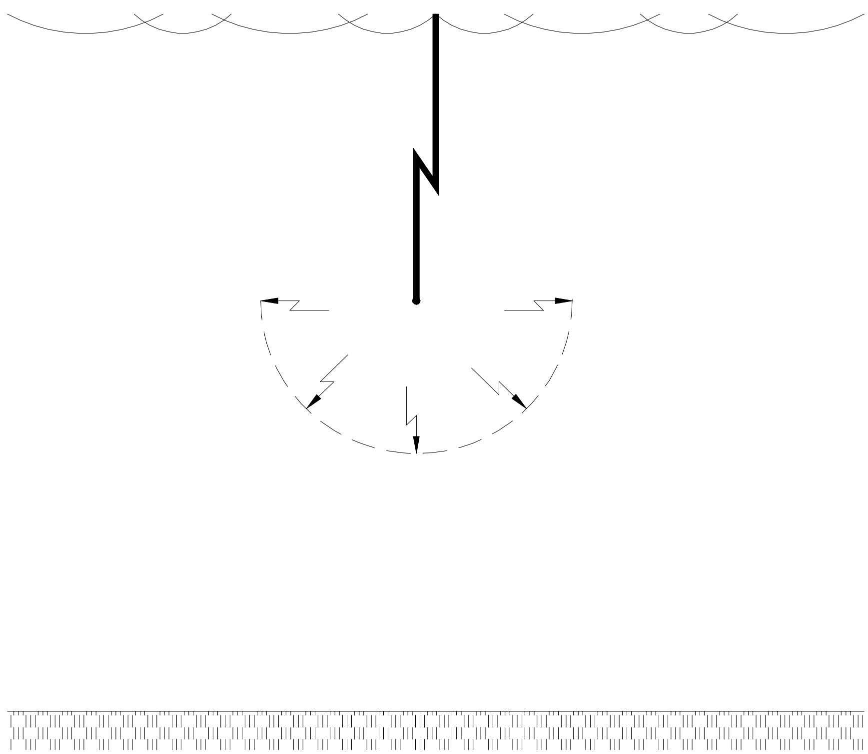

Fig. 1 A descending stepped leader seeking out an object to be struck.

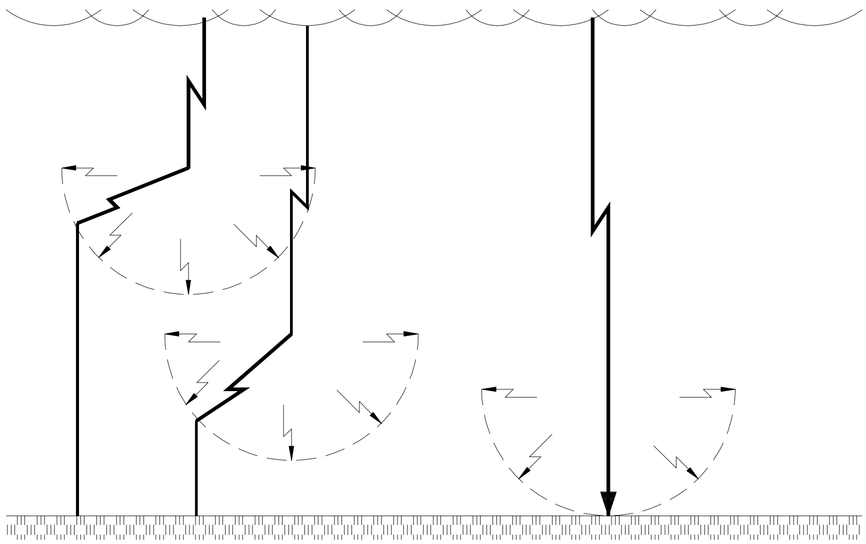

Fig. 2 The stepped leader striking different objects.

In Fig. 2, the taller pole makes its contact with the hemisphere around the leader tip, thus acting like a shield to a nearby shorter pole. However, if it originates at a point farther right, then it will either hit the shorter pole or the earth's surface. Figure 3 shows three stepped leaders of different strength descending on the pole pair. The hemisphere surrounding the left leader simultaneously touches both poles and the ground. This leader stroke will produce the critical return-stroke current which will have equal probability of striking the three objects. The stroke in the middle has lower prospective return-stroke current. This stroke strikes the shorter pole, signifying that the taller pole cannot shield the shorter pole below the critical current level. The leader stroke on the right has higher return-stroke current than that of the stroke on the left. This stroke strikes the taller pole. This suggests that the taller pole shields the shorter pole when the return-stroke current is above the critical current level; below this current level, the leader stroke will either strike the shorter pole or the ground. Figure 4 is similar to Fig. 3, except that the objects struck by lightning are horizontal wires (P=phase conductor, S=shield wire).

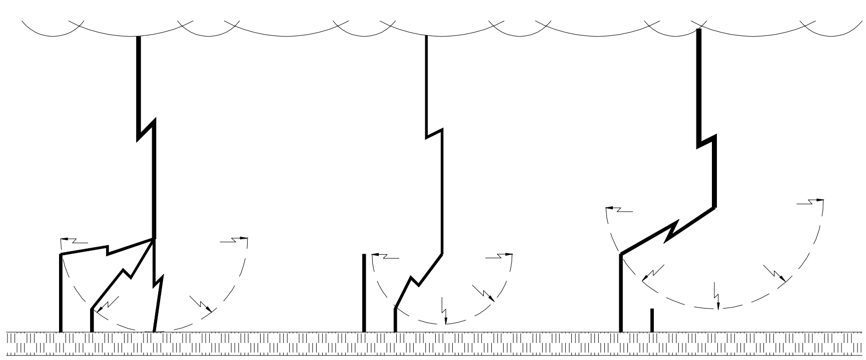

Fig. 3 Three leader strokes of varying strength descending upon a pole pair.

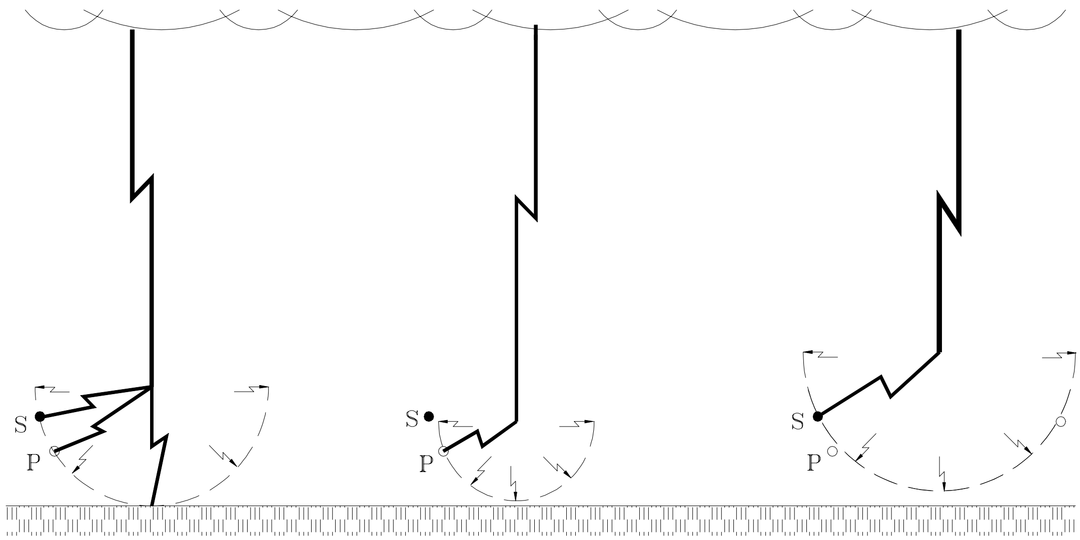

Fig. 4 Three leader strokes descending upon a pair of horizontal overhead lines.

In the above discussion, the stepped leader was originating at different points below the cloud and descending towards the earth with a hemisphere appended to its tip signifying the striking distance corresponding to the subsequent return-stroke current. It is easier for analysis to consider a stationary reference, such as the overhead power line and its towers. Figure 5 shows the cross-sectional view of horizontal conductors of varying heights above the earth's surface. The height of the first conductor on the left has smallest height and the last conductor on the right has the largest height.

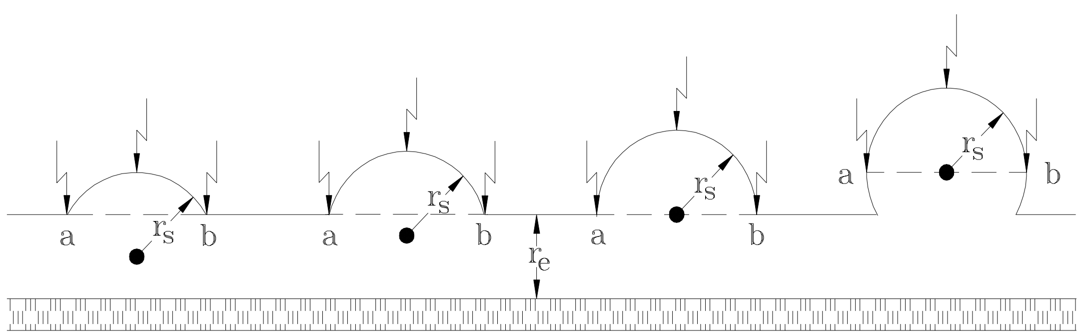

Fig. 5 Horizontal conductors of various heights above earth attracting lightning strokes.

It should be observed in Fig. 5 that the attractive width, ab, for the same stroke (i.e., same striking distance, r_s) increases with the height, h_p, of the conductor until at $h_p=r_s$, when $ab=2r_s$. The attractive width, ab, remains the same (i.e., $2r_s$) for $h_p \geq r_s$.

Attractive Width

It was shown in Chapter 4 that the attractive width of a single horizontal conductor above earth is:

$$ab = 2\sqrt{h_p(2r_s - h_p)} = 2\omega_p \quad \text{for } r_s > h_p, \text{ and}$$

$$ab = 2\omega_p = 2r_s \quad \text{for } r_s \leq h_p \ .$$

For a multiconductor line with a separation distance, d_p, between the outermost conductors, the attractive width will be $2\omega_p + d_p$.

To determine the attractive area of a vertical mast for a specified lightning stroke, a sphere is drawn around the mast tip, the radius, r_s, of the sphere being the striking distance corresponding to the specified return-stroke current, I_s. This sphere will cut the plane, which is r_s meters above the earth's surface, in a circle of radius, ω_t. The cross-sectional view of this construction is shown in Fig. 6. Any lightning stroke with return-stroke current of I_s or larger falling within the circle of radius of ω_t will hit the mast. Therefore, the attractive area of the vertical mast is $\pi\omega_t^2$.

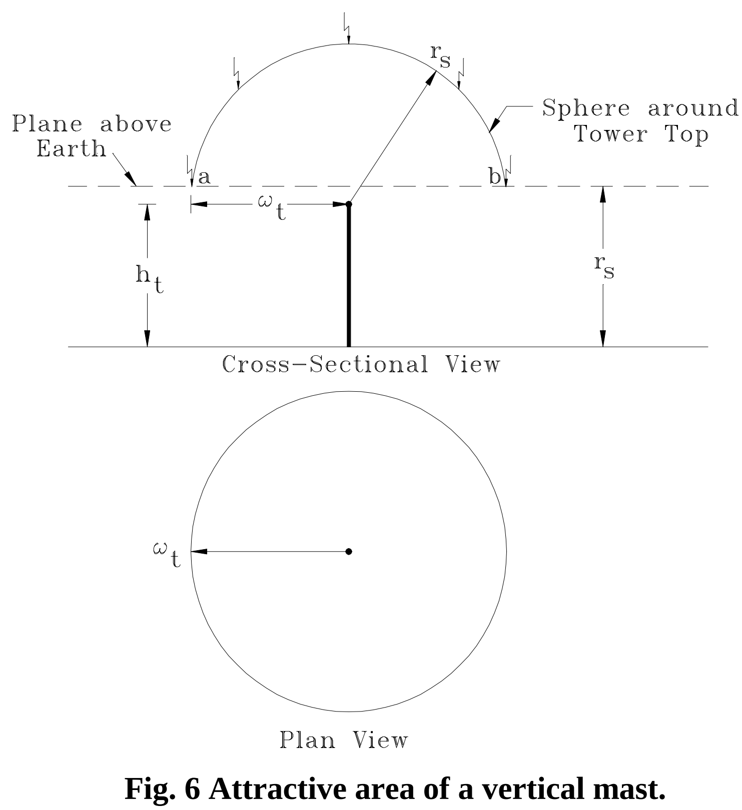

Fig. 6 Attractive area of a vertical mast.

The vertical towers and the horizontal phase conductors coexist for an overhead power line. In that case, there is a race between the towers and the phase conductors to catch the lightning stroke. Some lightning strokes will hit the towers and some will hit the phase conductors. Figure 7 illustrates how to estimate the attractive areas of the towers and the phase conductors.

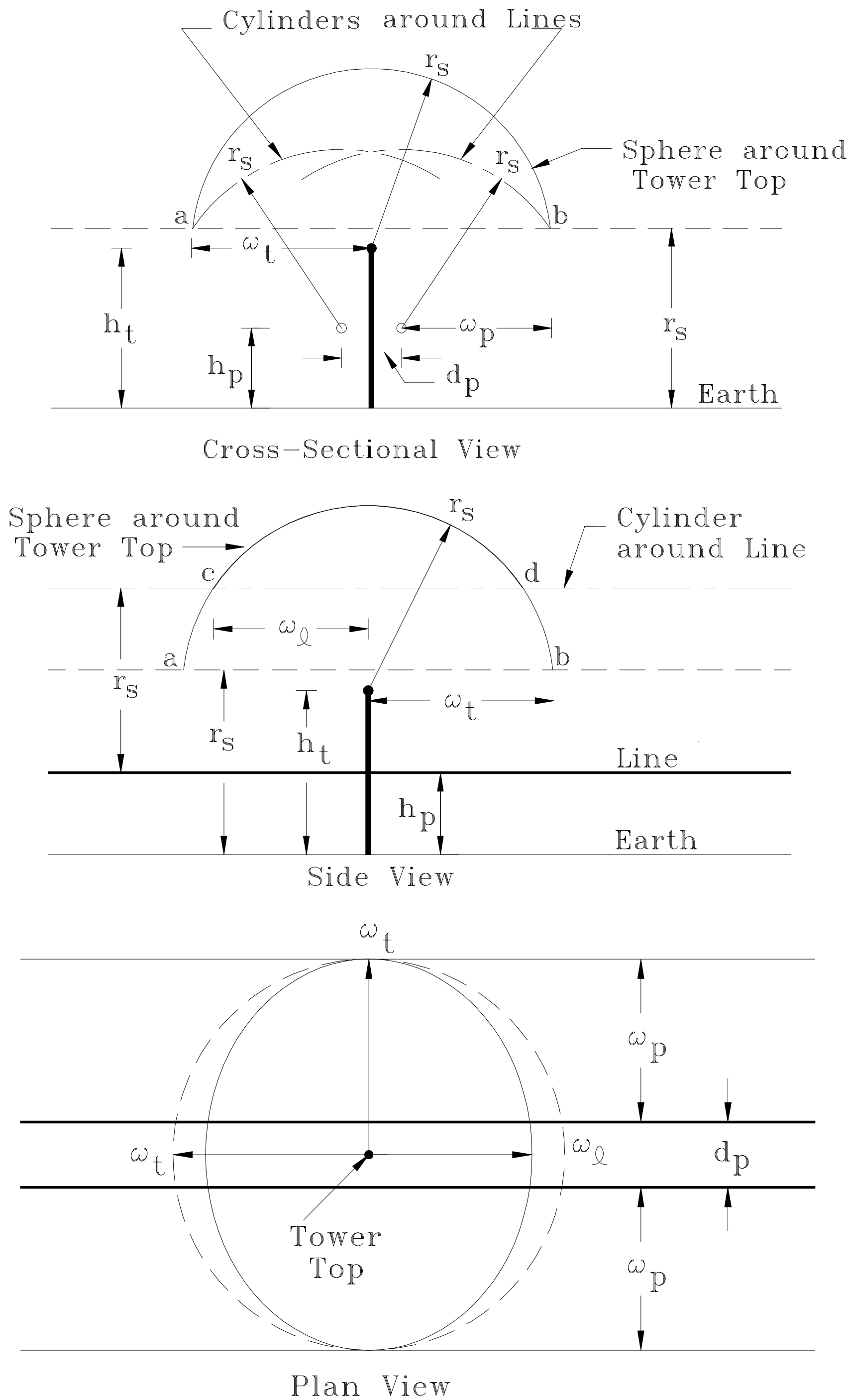

Fig. 7 Attractive areas of tower and phase conductors.

The tower and the two outermost phase conductors are shown in Fig. 7. In the cross-sectional view, a horizontal line is drawn at a distance r_s from the earth's surface, where r_s is the striking distance corresponding to the return-stroke current, I_s. A circle (cross-sectional view of a sphere) is drawn with radius, r_s, and center at the tip of the tower, cutting the line above the earth at a and b. Two circles (representing cylinders) are drawn with radius, r_s, and centers at the outermost phase conductors, cutting the line above the earth again at a and b. The horizontal distance between the tower tip and either a or b is ω_t. The side view of Fig. 7 shows where the sphere around the tower top penetrates both the r_s-plane (a and b) above ground and the cylinders around the outermost phase conductors (c and d). The projection of the sphere around the tower top on the r_s-plane is a circle of radius, ω_t, given by:

$$\omega_t = \sqrt{r_s^2 - (r_s - h_t)^2} \ .$$

The projection of the sphere on the upper surface of the two cylinders around the outer phase conductors will be an ellipse with its minor axis, $2\omega_\ell$, along a line midway between the two outer phase conductors and parallel to their axes; the major axis of the ellipse will be $2\omega_t$, as shown in the plan view of Fig. 7. ω_ℓ is given by:

$$\omega_\ell = \sqrt{r_s^2 - (r_s - h_t + h_p)^2} \ .$$

If a lightning stroke with return-stroke current, I_s or greater, falls within the ellipse, then it will hit the tower. It will hit one of the phase conductors if it falls outside the ellipse but within the width $(2\omega_p+d_p)$; it will hit the ground if it falls outside the width $(2\omega_p+d_p)$. Therefore, for each span length, ℓ_s, the attractive areas for the tower (A_t) and for the phase conductors (A_p) will be:

$$A_t = \pi \omega_t \omega_\ell, \quad \text{and}$$

$$A_p = (2\omega_p + d_p)\ell_s - A_t \ .$$

The above analysis was performed for the shielding current of the overhead line when the sphere around the tower top and the cylinders around the outer phase conductors intersect the r_s-plane above ground at the same points (points a and b in Fig. 7). In this case, $2\omega_t=2\omega_p+d_p$. The sphere and the cylinders will intersect the r_s-plane at different points for different return-stroke currents; their horizontal segments (widths) can be similarly computed. The equation for ω_t was given above. The equation for ω_p is given by:

$$\omega_p = \sqrt{r_s^2 - (r_s - h_p)^2} \ .$$

The computation is similar for shielded lines. h_p and d_p for the phase conductors are replaced by h_s and d_s, which are the shield-wire height and the separation distance between the shield wires, respectively. For a line with a single shield wire, d_s=0. Generally, shield wires are attached to the tower at its top. However, the effective height of the shield wire is lower than that of the tower due to sag. The effective height of the shield wire can be assumed to be:

$$h_s = h_{st} - \frac{2}{3}(\text{midspan sag}) \ ,$$

where h_{st} is the height of the shield wire at tower.

Placement of Shield Wires

Shield wires are installed on the premise that they will attract stepped leaders with prospective return-stroke currents exceeding a specified magnitude. This current is called the shielding current. Power lines are designed with an impulse voltage withstand level which corresponds to a specified return-stroke current. This is the critical current. Power-line insulation will fail if the return-stroke current exceeds the critical current. If the shielding current of the shield wire(s) is equal or below the critical current of the power line, there will be no insulation failure caused by lightning strikes. If the shielding current of the shield wire is higher than the critical current of the system, outages can be expected, caused by lightning strokes having return-stroke currents between the shielding current and the critical current. The concept of shielding current is shown in Fig. 8. The circular segments of radius r_s around P and S are the loci of the striking distance, r_s, corresponding to a return-stroke current, I_s. In Fig. 8a, the two circular segments intercept the parabola around P and the line, which is r_s m above earth, at the same point C. This means that the line is perfectly shielded for all lightning strokes with return-stroke currents of magnitudes I_s or higher. Figure 8b shows the case of a higher current, I_{s1}, with its correspondingly higher striking distance, r_{s1}. In this case, the line, P, is overshielded, because $I_{s1}>I_s$. The region BC is the overlapping region. For a lower current, I_{s2} ($I_{s2}<I_s$), shown in Fig. 8c, the two circles intercept each other at B, leaving P unprotected against lightning falling in the region BC, with return-stroke current magnitude between I_s and I_{s2}. However, there will be no line flashover if the designed impulse insulation level of the line is such that it can withstand voltages generated by lightning currents of magnitudes I_s and lower.

Figure 9 shows the cases where the shield wire is improperly placed. The case of unshielded line is shown in Fig. 9a as a reference case. The circles around the conductor, P, depict the striking distances to the line for various magnitudes of the return-stroke current. The intercepts of the circles with the parabola around P represent the attracting segments of lightning of various strengths. The case of properly placed shield wire is shown in Fig. 9b, where S is the shield wire. Here the circles around both P and S with radius, r_s, intercept the parabola around P and the line which is r_e m above the ground, all at the same point, C. r_s is the striking distance to P or S for a return-stroke current ,I_s, and r_e is the striking distance to ground for the same current. For lack of better data, $r_s=r_e$. I_s is the shielding current. The shield wire will intercept all currents, $I \geq I_s$. For perfect shielding, the line impulse insulation level should be able to withstand all lightning strokes with currents less than I_s. The shield wire is moved to the left in Fig. 9c, resulting in an undershielded line. The segment BC is the exposed region through which lightning may strike the conductor, P. The magnitude of the shielding current is higher for Fig. 9c. An overshielded line is shown in Fig. 9d. The segment BC is the overlapping area between the shield wire and the earth's surface. For a properly shielded line, lightning strokes falling in the region BC would have struck the earth. In Fig. 9d, the shielding current is lower than that in Fig. 9b.

In Fig. 8, the position of the shield wire is held fiexed; the magnitude of the return-stroke current is varied. In Fig. 9, the magnitude of the return-stroke current is held constant, while the position of the shield wire is varied.

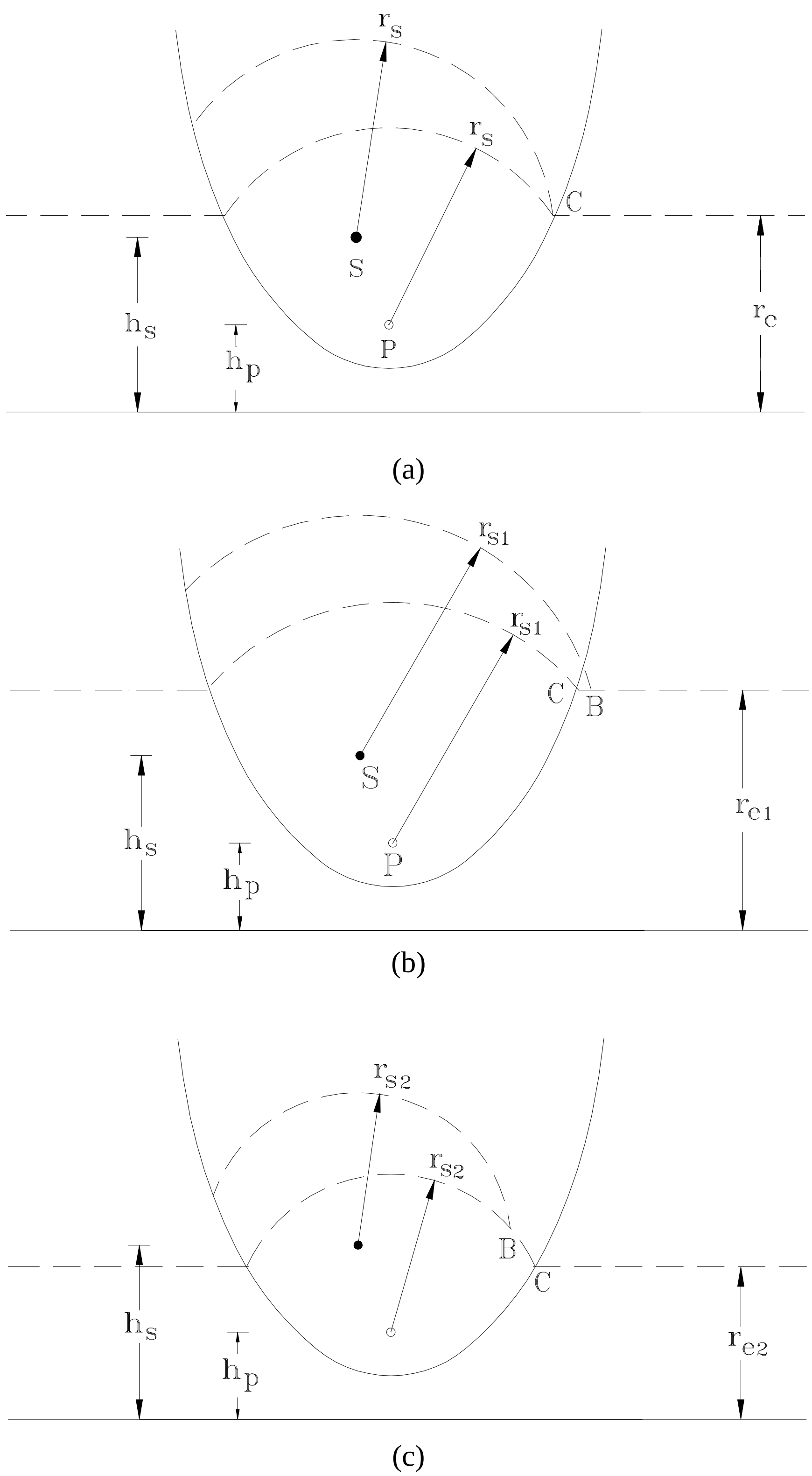

Fig. 8 Placement of shield wire.

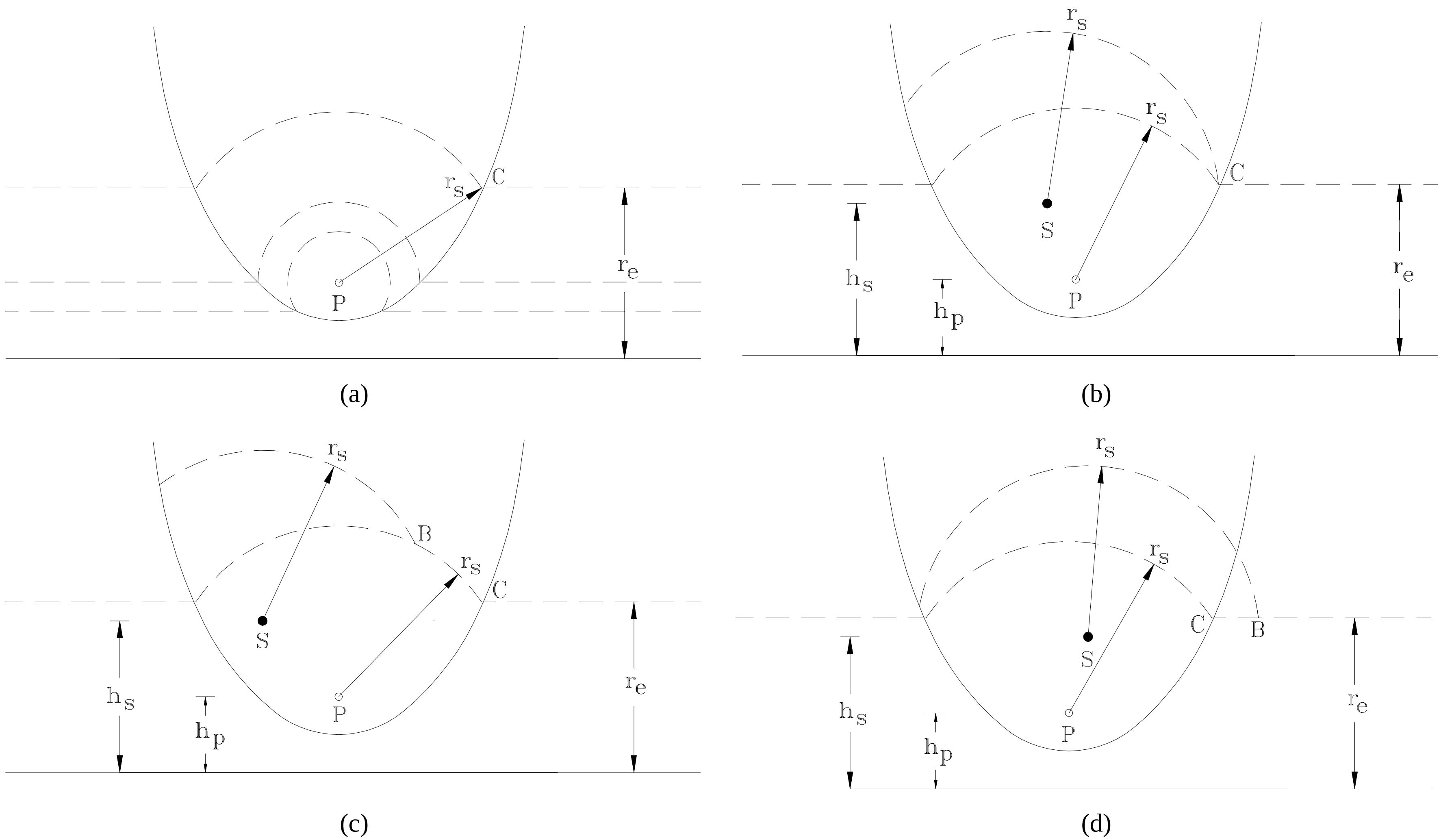

Fig. 9 Misplaced Shield wire.