APPENDIX A

Anchoring - Section 3103.9

Staking Analysis: vertical vs "at an angle"

The following is needed to understand why it is better to stake vertically rather than "at an angle":

a) Newton's Third Law Of Motion – "for every action there is an equal and opposite reaction". This means whenever an object pushes another object (a force in a direction) it gets pushed back in the opposite direction with the same force.
b) Engineering statics – the branch of mechanics concerned with bodies at rest and forces in equilibrium.
c) There is a normal compressive stress acting on the stake.
d) There is a frictional shear stress acting on the stake.
e) Assume there isn't a moment created anywhere on the stake.
f) Assume the soil conditions are the same for both cases.
g) Sine of 45 degrees = 0 .707 Cosine of 45 degrees = 0.707
h) Sine of 90 degrees = 1.0 Cosine of 90 degrees = 0.0

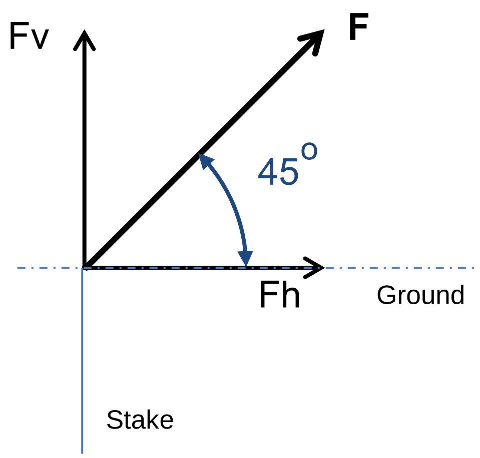
CASE 1: Vertical staking

There are two forces acting on the stake. (remember there isn't a moment created.) These forces are caused by the rope pulling on the stake, i.e., the tension in the rope. In the drawings that follow, this tension is labeled **F**. The first force is a normal compressive stress acting horizontally. This is Fh in the drawings. The second force is a frictional shear stress acting vertically. This is Fv in the drawings. The ability of the tent stake to remain stationary in the ground is a balance between these two forces. For our discussion, we are interested in the side of the stake closest to the tent.

The first area of interest is the spot where the rope attaches to the stake. The rope attaches at a 45 degree angle. This is important because from engineering statics, at this specific angle, we know the horizontal component of the rope tension, Fh, and the vertical component of the rope tension, Fv, are equal. Figure N1 shows the relationship between Fh, Fv and **F**. Figure N2 shows the statics analysis in relationship to the tent stake. Both Figure N1 and N2 are on the next page.

Con't.

Figure N1



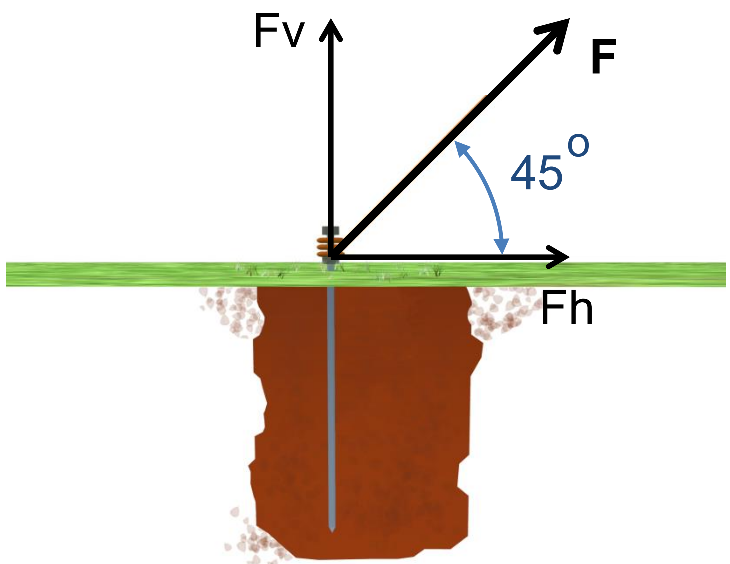
$Fh = \mathbf{F} \cos 45$

$Fh = \mathbf{F}\ 0.707$

$Fv = \mathbf{F} \sin 45$

$Fv = \mathbf{F}\ 0.707$

Figure N2



To finalize the mathematics and determine how much of the tent rope tension is pulling the stake to the right and how much force is pulling the stake vertically we need to know the tension in the rope. Let's say for the sake of discussion, the rope tension, **F**, equals 100 pounds. The horizontal component, Fh would equal F x 0.707. That is 100 x 0.707 = 70.7 pounds. The vertical component, Fv would equal F x 0.707. That is 100 x 0.707 = 70.7 pounds. This means almost 71 pounds of force is trying to pull that stake to the right and approximately 71 pounds of force is trying to pull the stake vertically up out of the ground.

Con't.

Now turn your attention to the portion of the stake which is embedded in the earth. The rope is trying to pull the stake to the right horizontally toward the tent. In this example, that force is 70.7 pounds. The soil is now being compressed by this pulling on the side of the stake nearest the tent. This is the normal compressive stress shown in the drawing below, Figure N3. From Newton's third law of motion, we know the force created by the stake is equal to the force pushing back from the soil. This means the soil is pushing back with a force of 70.7 pounds. The forces are the same, in this horizontal direction, and the tent stake is in equilibrium. Figure N4 shows Newton's third law of motion; a force diagram for both the stake on the soil and the soil on the stake.

Figure N3

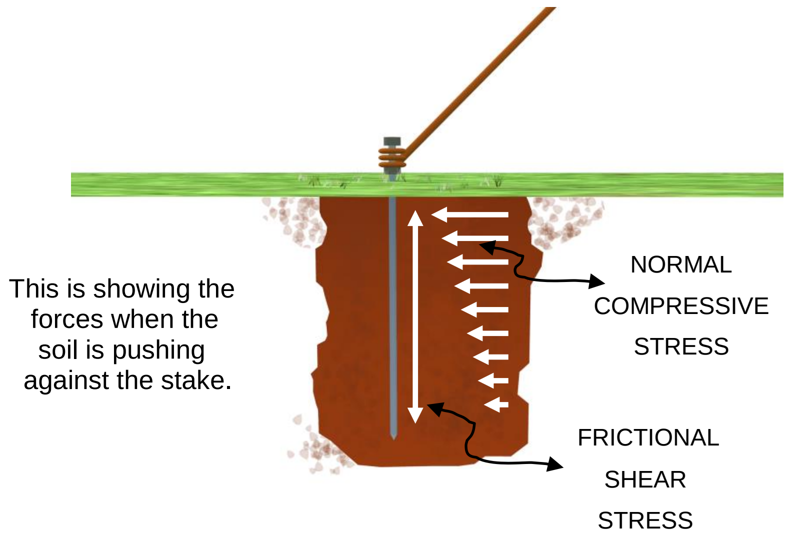
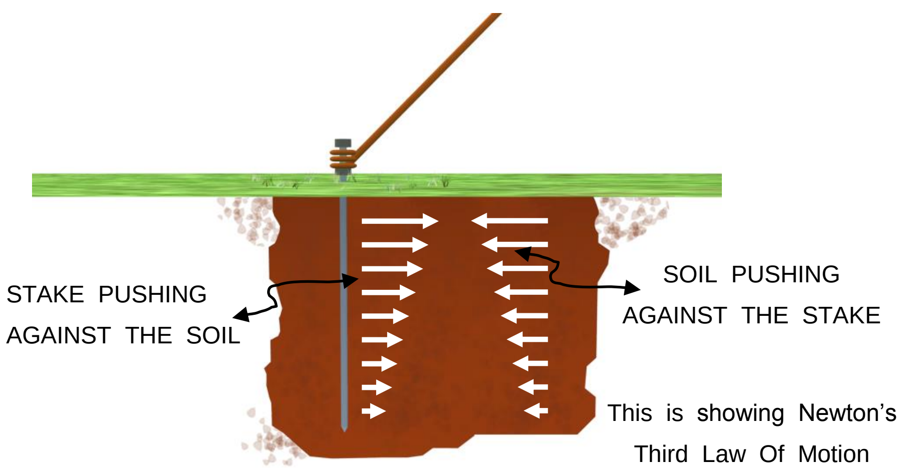


Figure N4



Con't.

The final item to study is the frictional shear stress which acts along the entire length of the stake. There is a bond between the stake and the soil and the strength of this bond is a function of the normal compressive stress. There is nothing pulling the stake into the ground so the forces creating this bond are only coming from the normal compressive stress in the horizontal direction. (I realize there is gravity, but the force of gravity affects everything under consideration so we are not treating it separately.) From the statics analysis shown in the preceding slides, we know the horizontal and vertical components of the rope tension are equal. The earth is pushing against the stake with 70.7 pounds of force. So the question is, “how strong is the bond between the stake and the soil?” The answer is “the frictional shear stress equals 70.7 pounds”. It is this equal balance between the normal compressive stress and the frictional shear stress which is producing the greatest resistance to the stake pulling out of the ground.

That concludes the study of Case 1. Compare what was just shown for a stake embedded vertically with the information for a stake embedded at a 45 degree angle. You’ll see that the stake at a 45 degree angle has a greater chance for failure and stake pull out.

CASE 2: Angle staking

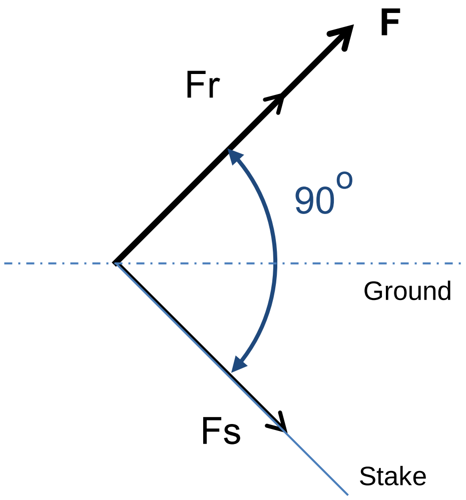
The stake is now embedded into the earth at a 45 degree angle. The rope is still attached at a 45 degree angle but with respect to the stake, a 90 degree angle is now created. In order to make the analysis easier, we are going to rotate the axes so that one of the axis directions runs along the length of the stake. This is Fs in Figure N5. The other axis runs along the length of the rope. This is shown as Fr in Figure N5. These are the two components of the rope tension, **F** acting on the stake. (remember there isn’t a moment created.) Figure N5 is on the next slide and shows these forces.

NOTE: in CASE 1, the axes didn’t have to be rotated because once the point of origin for the analysis was chosen (the spot where the rope attaches to the stake) one axis, Fv, aligned itself with the vertical stake and the other axis, Fh, aligned itself with the ground. This was fine for CASE 1 and no further adjustments had to be made.

Figure N6, also on the next slide, shows the statics analysis in relationship to the tent stake.

Con’t.

Figure N5



$Fs = \mathbf{F} \cos 90$

$Fs = \mathbf{F}\ 0.0$

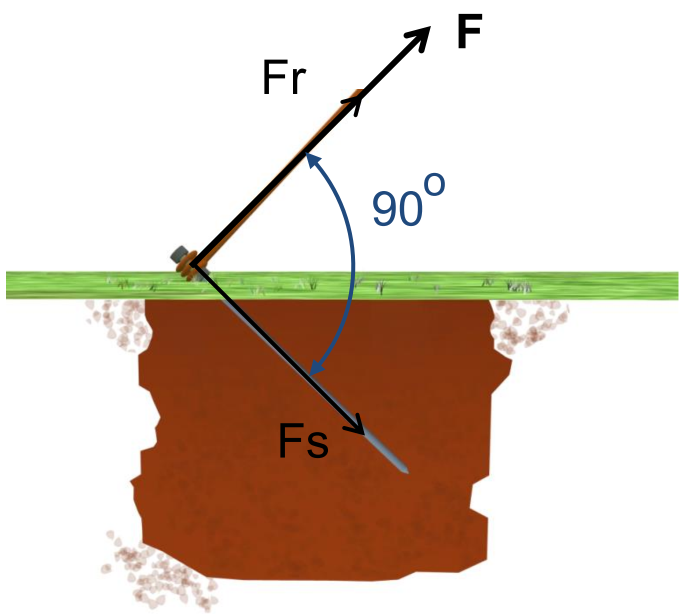
$\therefore\ Fs = 0$

$Fr = \mathbf{F} \sin 90$

$Fr = \mathbf{F}\ 1.0$

$\therefore\ Fr = \mathbf{F}$

Figure N6



In order to understand CASE 2, we need to compare drawings from both cases side by side. Remember the following for these comparisons:

1) The soil conditions are the same for both.

2) The stake has to withstand the same rope tension, **F**, for both.

3) The tension in the rope is 100 pounds; the same as CASE 1.

Con't.

First, in Figure N7, notice that the stake in CASE 2 doesn't extend as far into the ground as CASE 1. This is effecting the distribution of the forces (force profile) when the soil is pushing against the stake. Go back to Figure N4 and revisit the distribution of the forces for CASE 1. Next, take the force profile from CASE 1 and place it so it is acting on the stake in CASE 2. One can see that the force profile in CASE 2 is smaller because of the stake depth mentioned above and also, a part of it is sticking out of the ground. The portion above the ground is doing nothing to help keep the stake embedded in the ground. Figure N8 below, shows the smaller force profile for CASE 2.

Figure N7

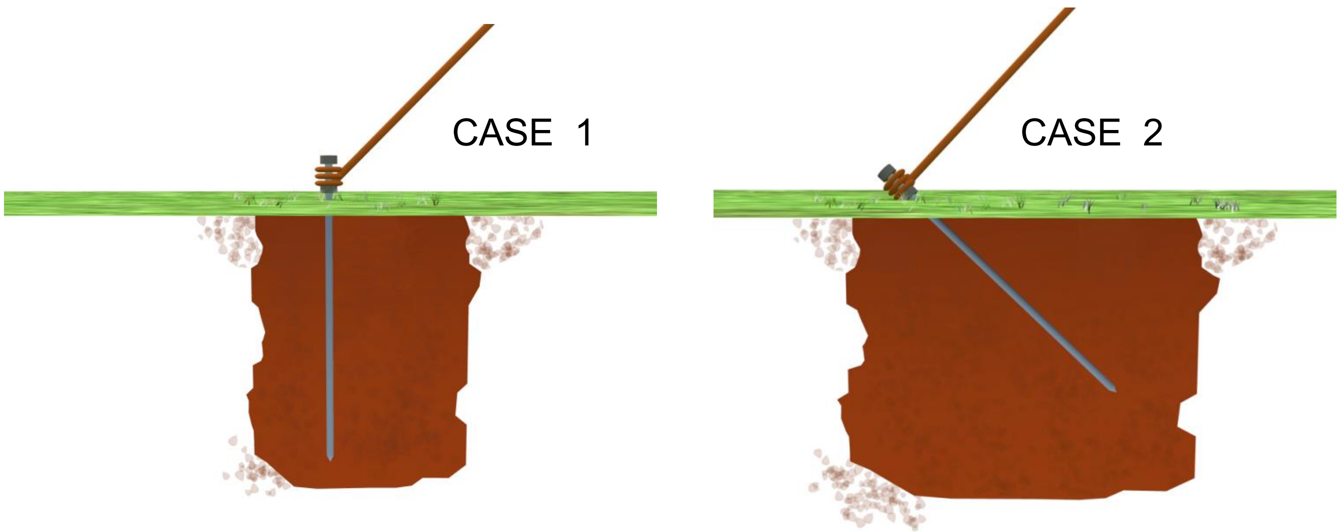
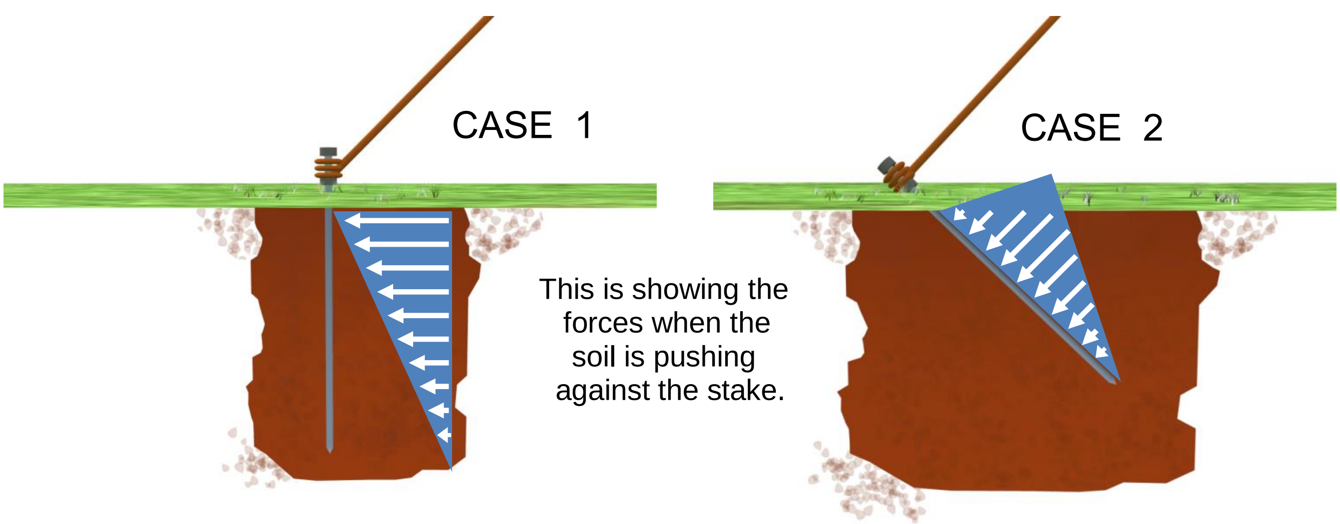


Figure N8



Con't.

A look at the normal compressive stress, Fr, and the frictional shear stress, Fs, further helps to explain why CASE 2 has a greater potential for stake pull out. Something very interesting is revealed in the mathematics. Assume once again that the rope tension, **F**, equals 100 pounds. Due to the 90 degree angle between the rope and the stake, there isn't any force component from the rope tension acting along the axis of the stake, i.e., the frictional shear stress, Fs, is zero. This is shown by the following equation from Figure N5; the frictional shear stress, Fs equals **F** x cos 90. The cos 90 = 0. Therefore, Fs = 0. One of our two force components, Fs, is doing nothing to hold that stake in the ground.

The other force component, Fr, the normal compressive stress, uses this equation from Figure N5; Fr equals **F** x sin 90. The sin 90 = 1. Therefore, Fr = **F**. We said the rope tension, **F**, was 100 pounds which means the normal compressive stress equals 100 pounds. The tension in the rope, **F**, still has two components, Fs and Fr, but because of the 90 degree angle, Fs equals zero and Fr is exerting every bit of the tension in the rope, 100 pounds, on the stake.

SUMMARY

One of our assumptions is the soil conditions are the same for both cases. The soil has to be able to handle approximately 71 pounds of stress in CASE 1. If the soil can provide this, the stake will stay embedded. In CASE 2, just because of the angle of the stake, the soil is being asked to handle approximately 29 more pounds of stress, for a total of 100 pounds. The soil in CASE 2 is being asked to do more.

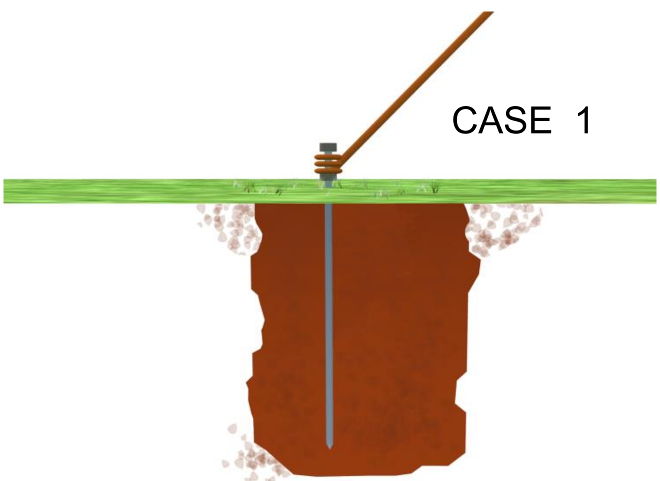
Finally, let's make one more assumption. We all know there are many different types of soil. Let's assume the soil for our two cases can only handle 71 pounds of stress. The tent with the stakes embedded vertically will remain in the ground. If the same tent has the stakes embedded at a 45 degree angle, the normal compressive stress on a stake will exceed the soil's compressive strength. When this happens, the soil will start to break apart and a bulge of soil will start to form between the stake and the tent. The soil has failed and the stake will start to move toward the tent. Once movement begins, stake pull out is likely.

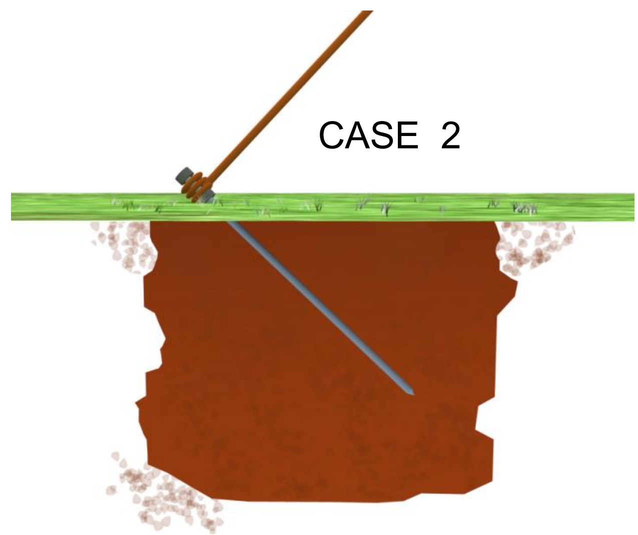
Con't.

CONCLUSION

By comparing our two cases side by side, it is clear that the soil in Case 2 with the stake embedded at a 45 degree angle has to be stronger. The Indiana Fire Code does not say one has to embed a tent stake vertically. You can embed that stake at any angle you want. However, we have just shown why it is better to stake vertically rather than at an angle.

* This has been an attempt to explain this topic in a way that everyone could understand. The actual engineering study was conducted by the University of Illinois at Urbana-Champaign, School of Engineering in 2006 and can be found by viewing the website for The Tent Rental Division, Industrial Fabrics Association International.





THIS IS BETTER