

From the Ground Up

Cathy Bazán-Arias



Courtesy of GAI Consultants, Inc.

**Key Concepts
from Previous Chapters**

- ② Redesign
- ①① Loads
- ①① Foundation
- ①① Construction Materials—Characteristics
- ①③ Stress

The Leaning Tower of Pisa is a famous example of what can go wrong when engineers and architects don't know what they are building on. Even during its construction, which began in 1173, the Tower began to lean to one side. We now know that the Tower leaned because the soil beneath it, which contained a lot of sand, could not bear the load of the structure. Engineers have kept the Tower standing through the centuries by continuously repairing it, restabilizing it, and even altering the soil.

It's a lot more cost-effective to make sure the soil underneath can support the structure's load long before construction starts. As a geotechnical engineer, that's a big part of my job. My name is Cathy Bazán-Arias, and I'm a senior engineer at GAI Consultants, Inc., an engineering firm based in Pittsburgh, Pennsylvania.

My company provides engineering expertise on a wide range of projects, from designing and building dams to upgrading electric transmission lines to improving mass-transit systems. Our clients include private companies, government agencies, and even international organizations.

As a little girl growing up in Mexico, I knew that I wanted to become an engineer. My father was a professor of engineering at a major university in Mexico City. Though engineering was not considered a profession for women, my father would take me to work with him. He always found ways to involve me in his engineering projects. We moved to the United States when I was starting eighth grade. There I found more opportunities to get involved with student engineering and science programs. And I met more female engineers who I took as role models. I studied civil engineering at the University of Pittsburgh for my undergraduate degree. Then I went on to get a master's degree and a Ph.D. in geotechnical engineering there as well.

A Matter of Matter

The prefix “geo” is a Greek word that means Earth or land. So it makes sense that geotechnical engineers specialize in designing how structures or underground parts of structures interact with the land they are standing on. To do my job, I need to know all about a structure's geometry, materials, and loads. As you can see, geotechnical engineering is closely related to structural engineering. I have training in both disciplines, and that dual training often comes in handy.

One project I'm working on illustrates how my dual training helps. My team recently took on a project improving an electric power transmission line. Transmission lines carry electrical current from a power station—where the electricity is generated—over long distances to the communities that will use the electricity. The towers that hold up the electrical lines are spaced about every 300–500 yards for hundreds of miles, and must be designed to stand on a wide range of terrains—including forests, agricultural lands, and rocky foothills.

In this photo of a transmission tower under construction, you can see the above-ground structure of the tower quite well. But what keeps it standing? The visible part of the tower would not be stable without a foundation. If there is too much movement of the tower base due to poor foundation performance, there could be an above-ground structural failure and wire breakage. If wires break, the whole power line will stop working.



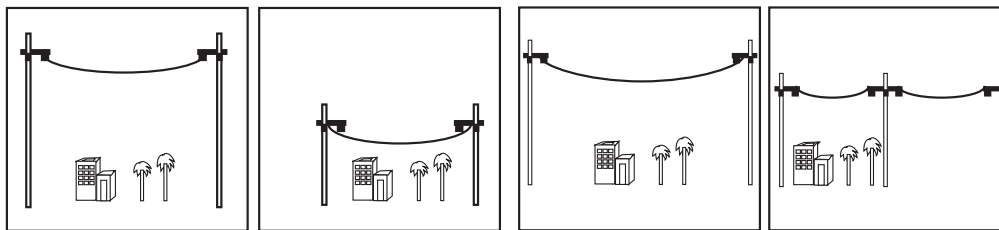
Courtesy of GAI Consultants, Inc.

In the Northeastern United States, it is often necessary to upgrade transmission lines. Typically, this requires constructing some new towers and renovating some older ones. In either case, we must make sure that the towers' components—above-ground and below-ground—are constructed with strong enough materials. We must also verify that the towers are on soils that will support them without excessive movement. This means understanding how the soils and the structure will interact.

Tower Design Criteria

Electric power transmission lines have been around for a long time. We don't need to reinvent the wheel, but we do want to improve upon older designs. Transmission structures are typically made from steel, wood, and concrete. And they are usually tall and narrow. The same is true for the new towers we are designing. They will be 90–100 feet tall on average. The taller the towers, the fewer towers that are needed over any given distance. This is because the current carrying wires will be strung from tower to tower.

There will be some slack in the wires, and the wires will hang lowest at the farthest point between the two towers. If the towers are too short and spaced too far apart, the current carrying wire will hang dangerously close to the ground, tree tops, or other human activity. But if the towers are very tall, we can space them farther apart and still not leave the sagging wire near people, because it is still high. At the same time, we want the towers themselves to be as narrow as possible. A narrow tower requires less space on the ground. This is advantageous because the towers may go through populated areas where land prices are high. Narrow, sleek towers will also be less obtrusive on the landscape than bulky towers. The towers' neighbors will appreciate that!

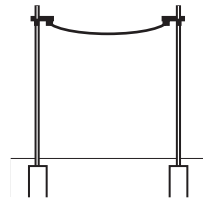


Taller transmission towers can have greater distances between them.

In this case, three short towers are needed to cover the same distance that two tall towers cover.

Even though the towers will be tall and narrow, they must be quite strong. They will have to remain standing during high winds. And in the Northern United States, the line may get loaded with snow and ice in the winter. Ice loading is a big concern. Ice can get very thick and add considerable weight to the line. Ice loading has torn down towers in the past, leading to major electrical outages that affected millions of people. We want to do everything we can to avoid a major outage on our lines.

The foundation for each tower varies, but a typical foundation looks something like the diagram below. The structure's vertical poles rest on cylindrical foundations, which are embedded in the ground at a depth between 15 and 20 percent of the height of the pole. So a 50-foot pole will have a foundation 10 feet underground.



The most common material for transmission-line foundations is reinforced concrete. Steel may be used if the soils in the area will not bear the weight of concrete. Steel is also used for the foundations in areas where it is hard to get the required materials into the construction area by truck. In this case, the foundation components have to be flown by helicopter. The geometry of the foundations may change depending on how the tower's load needs to be distributed, so that the soil can support it.

Selecting Materials

A large part of the job involves selecting the right materials for the foundation and the above-ground portion of the towers. We know that the materials we will use to build the towers are most likely going to be steel, concrete, and wood. These materials have been used to build electric power transmission lines for a long time. But there are many, many types of each material. We want to choose the types that are ideally suited for the unique climates and terrains that our line will traverse, and the variety of loads they will experience.

To select the very best material for our purposes, we need to compare how different materials behave under stress. The stresses could be a result of compression, tension, torsion, or shearing forces. For a long time, engineers have studied how commonly used materials behave under such stresses and documented the results.

That means that we don't have to test commonly used materials ourselves. We usually look up a material in a reference manual to learn how it behaves under different types of stresses in different conditions. If we are using a new material, or are using a material in a new and untested way, we must test those materials ourselves.

In addition to comparing how materials behave, my team will also compare performance and cost. Performance means how long the material will do its job well. The towers will experience a lot of wear and tear due to seasonal temperature fluctuations, snow, rain, and sun, and even the chemistry of the soil in which they are embedded. Materials respond differently to these stressors. Wood breaks down over time, and steel can corrode. We know that the towers will need regular maintenance to stay in working order. But if they need frequent maintenance, in addition to the normal care, those costs could add up.

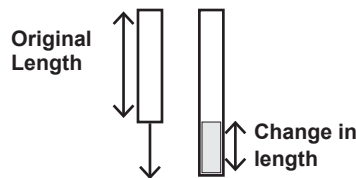
The selection of the right material also requires us to determine how long we want the structure to last, and how much money we can spend. Many high-performance materials come with a high price. And we often don't need a high-performance material to do the job well. If we determine we only need a tower to stand for ten years, a lower-grade steel may serve our purposes just as well as a more expensive high-grade steel. However, a higher-performance material may save money over time because it will require less maintenance. Based on the performance criteria, we can determine the most economical material that will still get the job done well.



Courtesy of GAI Consultants, Inc.

Every material changes shape, or deforms, in response to stress. It's easy to visualize this deformation in a rubber band. When you pull on both ends of a rubber band, you apply stress to the material. In response, the rubber band increases in length. **Strain** is a measure of how much a material deforms as compared with its original size. Strain can be calculated using the following equation:

$$\text{Strain } (\epsilon) = \frac{\Delta L}{L}$$



ΔL = **Change in length** of a material after stress is applied
 L = **Original length** of the material



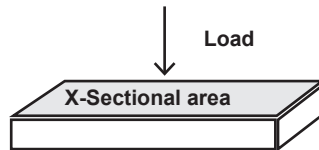
Editor's Note Stress and Strain

When selecting materials, Dr. Bazán-Arias must compare the strength of materials. **Strength** is a calculation of how much stress a material can support without deforming in a way that compromises the integrity of the material. As you recall, stress is the load or force per unit area of material. Stress is calculated with the following equation:

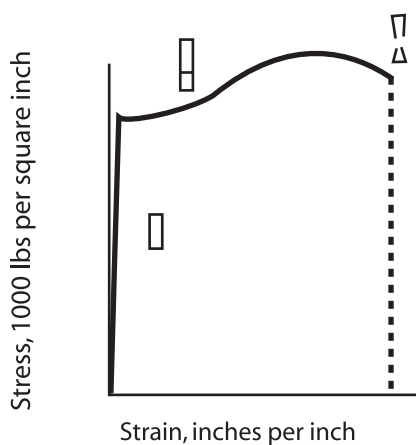
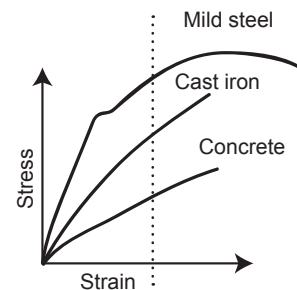
$$\text{Stress } (\sigma) = \frac{F}{A}$$

$$F = \text{Load}$$

$$A = \text{Cross-sectional area}$$



When engineers test materials, they often subject a sample of the material to different stresses and plot how much a material strains on a graph. These graphs, like the one shown on the right, are called stress-strain curves. Engineers can get a lot of useful information about how a material behaves by looking at a stress-strain curve.



Point 1 to Point 2 elastic deformation: As you can see, this part of the graph is very straight and steep. This means that as stress increases, strain increases very slowly. In other words, the material does not deform very much, and when the stress is removed, the material returns to its original shape. This is called elastic deformation.

Point 2 is the elastic limit: After this point, the material does not return to its original shape.

Point 2 to Point 3 plastic deformation: When stress reaches the level indicated at point 2, called the elastic limit, the material begins to behave very differently. Strain increases very quickly with even small increases in stress. For example, when a piece of metal reaches this point, it starts to stretch like taffy. Furthermore, the deformation is permanent. Once the stress passes the elastic limit, the material will not return to its original form.

Point 3 is the failure point: The material breaks, so it is no longer possible to increase the level of stress.

Bringing It Back Down to Earth

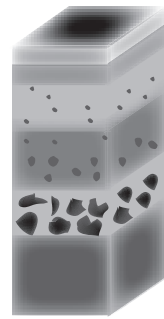
To make our material selections, we must know what types of soils we'll be building on. Depending on the type of terrain we find, we may need to alter the design of the foundation, and possibly the tower as well.

To learn about the different types of terrains that we may encounter while building our towers, my team hires scientists who have spent years studying the soils in the area. Because the transmission line project covers such a wide range of terrains, it would require a lot more work, and time, for my team to learn everything we need to know about the land in the region by doing our own research. It's much more cost effective to hire a consultant who has already done the research.

The underground structure of the towers will extend into the substrata, an underground layer of Earth. The substrata may contain rock, gravel, sand, clay, silt, decomposing plant matter, or any combination of these. Each type of soil behaves differently under stress, and the same soil types may behave differently in different conditions.

Two soil types we commonly encounter are sand and clay. Sand is very strong when it's wet. When the sand is dry, though, it can't hold much weight at all. If you've ever walked on a sandy beach or stepped into a child's sand box, then you've experienced how sand gives way under your weight. Clay soils, on the other hand, can be very strong, but if the load of a structure is not distributed well over the clay, it may compress the clay. If the clay is compressed, part or all of the structure could sink.

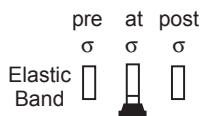
The behavior of the soils in response to different stresses has also been studied and documented. The properties of different soil types and how they respond to different stresses can be described by stress-strain curves. These curves are critical to determine how a soil may behave when subjected to different types of loads.



As soon as my team has information about the terrain and understands the soil and its load limitations, we can start to make decisions about how to design the foundation in terms of materials and structural geometry. Sometimes we learn that we need to site a tower in a different location because the soil won't bear the load of the tower, regardless of how well we design it! If we can't change the location of the tower, we may attempt to dig out some of the problematic substrata and replace it with stronger material.

When it comes to structures, what you see is not all you get. An underground system, which includes both naturally occurring and human-made materials, is necessary to keep a structure standing. As a geotechnical engineer, I've had the pleasure of applying my academic knowledge to the task of building structures from the ground up.

○ **Terms of Failure Analysis** ○

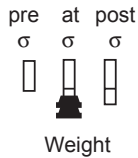


Elastic Deformation:

Material returns to its original shape after stress is applied.

Elastic Limit:

Point where elastic deformation ends and plastic deformation begins.

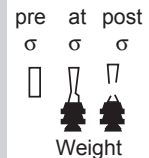


Plastic Deformation:

Material does not return to its original shape after stress is applied.

Failure Point:

Point where the material breaks or fractures.





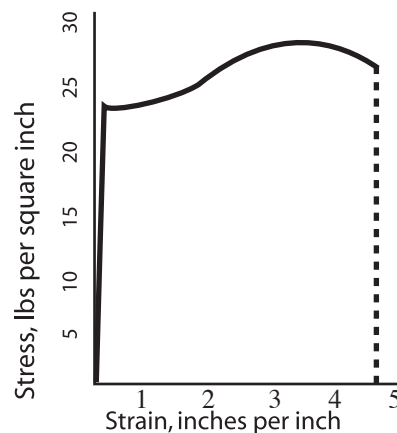
What's the Story?

1. Dr. Bazán-Arias is a geotechnical engineer by training, but she also has some expertise in structural engineering. Why does she believe having both is helpful?
2. What are the major factors that engineers consider when selecting materials for a job?
3. What kinds of information can engineers get by looking at stress-strain curves?



Designing with Math and Science

4. Look at the stress-strain curve below. How much does the material strain under 25 PSI of stress? Will the material return to its original shape after a stress of this magnitude has been applied?
5. What is the elastic limit of the material, and how can you tell? How will the material behave under loads higher than the elastic limit?



Connecting the Dots

6. Foundations are important parts of the structural designs described in the three previous chapters. Write a one-sentence description of each of the following structures' foundations: 1. The Leonard P Zakim Bridge; 2. The Burj Dubai; 3. A house; 4. A transmission tower.



What Do You Think?

7. Dr. Bazán-Arias also designs landfills for GAI Consulting. Do some research in the library or on the Internet and write two paragraphs about landfill design. In your response, explain some of the decisions that engineers designing a landfill may have to make in terms of location, material selection, and structural geometry.