CASE STUDY 7.3

Classic Case: Tacoma Narrows Suspension Bridge

The dramatic collapse of the Tacoma Narrows suspension bridge in 1940, barely four months after completion, was a severe blow to the design and construction of large-span bridges. It serves as a landmark failure in engineering history and is, indeed, a featured lesson in most civil engineering programs. The story of the collapse serves as a fascinating account of one important aspect of project failure: engineering's misunderstanding of the effect that a variety of natural forces can have on projects, particularly in the construction industry.

Opening in July 1941, the Tacoma Narrows Bridge was built at a cost of \$6.4 million and was largely funded by the federal government's Public Works Administration. The purpose of the bridge was essentially viewed as a defense measure to connect Seattle and Tacoma with the Puget Sound Navy Yard at Bremerton.[19] As the third-largest single suspension bridge in the world, it had a center span of 2,800 feet and 1,000-foot approaches at each end.

Even before its inauguration and opening, the bridge began exhibiting strange characteristics that were immediately noticeable. For example, the slightest wind could cause the bridge to develop a pronounced longitudinal roll. The bridge would begin to lift at one end and, a wave action would "roll" the length of the bridge. Depending upon the severity of the wind, cameras could detect up to eight separate vertical nodes in its rolling action. Many motorists crossing the bridge complained of acute seasickness brought on by the bridge's rising and falling. So well-known to the locals did the strange weaving motion of the bridge become that they nicknamed the it "Galloping Gertie."

That the bridge was experiencing increasing and unexpected difficulties was clear to all involved in the project. In fact, the weaving motion of Galloping Gertie became so bad as summer moved into fall that heavy steel cables were installed externally to the span in an attempt to reduce it. The first attempt resulted in cables that snapped as they were being put into place. The second attempt, later in the fall, seemed to calm the swaying and oscillating motion of the bridge initially. Unfortunately, the cables would prove to be incapable of forestalling the effects of the dynamic forces (wind) playing on the bridge; they snapped just before the final critical torsional oscillations that led to the bridge's collapse.

On November 7, 1940 a mere four months after the bridge's opening and with winds of 42 miles per hour blowing steadily, the 280-foot main span that had already begun exhibiting a marked flex went into a series of violent vertical and torsional oscillations. Alarmingly, the amplitudes steadily increased, suspensions came loose, the support structures buckled, and the span began to break up. The bridge seemed to have come alive, struggling like a bound animal, and was shaking itself apart. Motorists caught on the bridge had to abandon their cars and crawl off of it, as the side-to-side roll had become so pronounced—45 degrees in either direction, causing the sides of the bridge to rise and fall more than 30 feet—that it was impossible to traverse the bridge on foot.

After a fairly short period of time in which the wave oscillations became incredibly violent, the suspension bridge simply could not resist the pounding and broke apart. Observers stood in shock on either side of the bridge and watched as first large pieces of the roadway, and then entire lengths of the span rained down into the Tacoma Narrows below. Fortunately no human lives were lost, since the bridge had been closed in the nick of time.

The slender 12-meter-wide main deck had been supported by massive 130-meter-high steel towers comprised of 335-foot-long spans. These spans managed to remain intact despite the collapse of the main span. The second bridge (TNB II) would end up making use of these spans when it was rebuilt shortly thereafter, by a new span stiffened with a web truss.

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Following the catastrophic failure, a three-person committee was immediately convened to determine the causes of the Tacoma Narrows Bridge collapse. The board consisted of some of the top scientists and engineers in the world at that time: Othmar Ammann, Theodore von Karman, and Glenn Woodruff. While satisfied that the basic design was sound and the suspension bridge had been constructed competently, these experts nevertheless were able to quickly uncover the underlying contributing causes to the bridge collapse:

- **Design features**—The physical construction of the bridge contributed directly to its failure and was a source of continual concern from the time of its completion. Unlike other suspension bridges, one distinguishing feature of the Tacoma Narrows Bridge was its small width-to-length ratio—smaller than any other suspension bridge of its type in the world (although almost one mile in length, the bridge was only constructed to carry a single traffic lane in each direction). That ratio means quite simply that the bridge was incredibly narrow for its long length, a fact that was to contribute hugely to its distinctive oscillating behavior.
- **Building materials**—Another feature of the construction that was to play an important role in its collapse was the substitution of key structural components. The original plans called for the use of open girders in the construction of the bridge's sides. Unfortunately, at some point a local construction engineer substituted flat, solid girders that deflected the wind rather than allowing for its passage. The result was that the bridge caught the wind "like a kite" and adopted a permanent sway. In engineering terms, the flat sides simply would not allow wind to pass through the sides of the bridge, reducing its wind drag. Instead, the solid, flat sides caused the wind to push the bridge sideways until it had swayed enough to "spill" the wind from the vertical plane, much as a sailboat catches and spills wind in its sails.
- **Bridge location**—A final problem with the initial plan lay in the actual location selected for the bridge's construction. Although the investigating committee did not view the physical location of the bridge as contributing to its collapse, the location did play an important secondary role through its effect on wind currents. The topography of the Tacoma Narrows over which the bridge was constructed was particularly prone to high winds due to the narrowing down of the land on either side of the river. The unique characteristics of the land on which the bridge was built virtually doubled the wind velocity and acted as a sort of wind tunnel.

Before this collapse, not much was known about the effects of dynamic loads on structures. It had always been taken for granted in bridge building that static load (downward forces) and the sheer bulk and mass of large trussed steel structures were enough to protect them against possible wind effects. It took this disaster to firmly establish in the minds of design engineers that dynamic, and *not* static, loads are really the critical factor in designing such structures.

The engineering profession took these lessons to heart and set about a radical rethinking of their conventional design practices. The stunning part of this failure was not so much the oscillations, but the spectacular way in which the wave motions along the main span turned into a destructive tossing and turning, which led finally to the climax in which the deck was wrenched out of position. The support cables snapped one at a time, and the bridge began to shed its pieces in larger and larger chunks until the integrity was completely compromised.

Tacoma Narrows Bridge: The Postmortem

Immediately following the bridge's collapse, the investigating board's final report laid the blame squarely on the inadequacy of a design that did not anticipate the dynamic properties of the wind on what had been thought a purely static design problem. Although longitudinal oscillations were well understood and had been experienced early in the bridge's construction, it was not until the bridge experienced added torsional rolling movements that the bridge's failure became inevitable.

One member of the board investigating the accident, Dr. Theodore von Karman, faced the disbelief of the engineering profession as he pushed for the application of aerodynamics to the science of bridge building. It is in this context that he later wrote his memoirs, in which he described his dilemma in this way: "Bridge engineers, excellent though they were, couldn't see how a science applied to a small unstable thing like an airplane wing could also be applied to a huge, solid, nonflying structure like a bridge."

The lessons from the Tacoma Narrows Bridge collapse are primarily those of ensuring a general awareness of technical limitations in project design. Advances in technology often lead to a willingness to continually push design envelopes in an effort to achieve maximum efficiency. The problem with radical designs, or even with well-known designs used in unfamiliar ways, is that their effect cannot be predicted using familiar formulae. In essence, a willingness to experiment requires that designers and engineers begin working to simultaneously develop a new calculus for testing these designs. It is dangerous to assume that a technology that has worked well in one setting will work equally well in another, particularly when other variables in the equation are subject to change.

The Tacoma Narrows Bridge collapse began in high drama and ended in farce. Following the bridge's destruction the state of Washington discovered, when it attempted to collect the $6 million insurance refund on the bridge, that the insurance agent had simply pocketed the state's premium and never bothered obtaining a policy. After all, who ever heard of a bridge the size of the Tacoma Narrows span collapsing? As von Karman wryly noted, "He [the insurance agent] ended up in jail, one of the unluckiest men in the world."[20]

Questions

1. In what ways were the project's planning and scope management appropriate? When did the planners begin taking unknowing or unnecessary risks? Discuss the issue of project constraints and other unique aspects of the bridge in the risk management process. Were these issues taken into consideration? Why or why not?
2. Conduct either a qualitative or quantitative risk assessment on this project. Identify the risk factors that you consider most important for the suspension bridge construction. How would you assess the riskiness of this project? Why?
3. What forms of risk mitigation would you consider appropriate for this project?