Walking in San Francisco, near Land's End, we Geology students were shown a crumbly rock seemingly made of mud and dust. *This* we were told, *was Serpentinite* –

The decomposed stone was shockingly easy to turn to dust in the hand. 15 years in the wind and rain will turn this: into this:

Serpentinite – from Geology 21A Handout

K. Wiese

Weathered Serpentinite (from Sonoma)

S. McGuinney

"The South Tower of the Golden Gate Bridge," we were told, "is built on Serpentinite.

Dr. Lawson, or:
How I Learned To Stop Worrying and Love the Bridge

Geology 21A

Spring, 2014

by Dan Priven

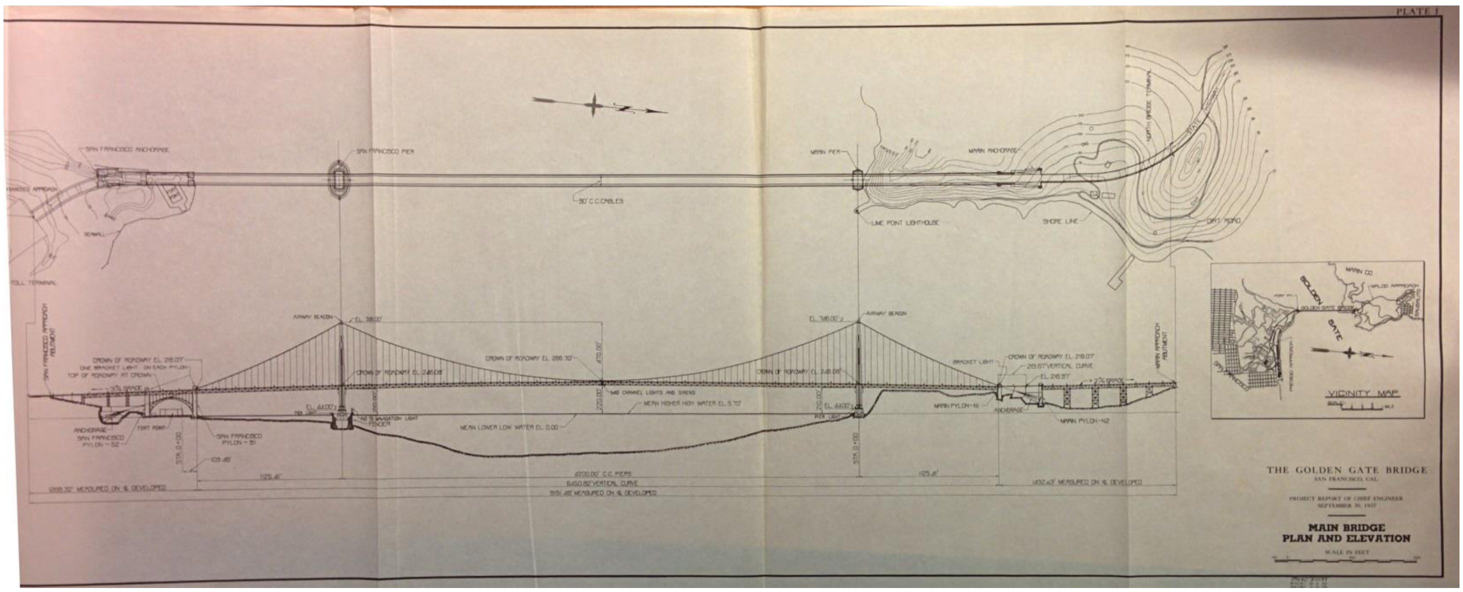
Alliterative Abstract:

"Stop! Serpentinite!" Says Sensationalist Stanford Sage

"Bunkum!" Bellows Better Berkeley Brain

Brief Background Befitting Bridge Beginners

The Golden Gate Bridge was completed in 1937, but planning was well under way ten years prior, and construction began in 1933. It was the longest and most complicated suspension bridge ever built at the time, and it required new techniques and technologies which were unproven. The most public controversy concerning the feasibility of bridge regarded the placement of the foundation - called a pier - of the south tower (to the left, below)



(Strauss, 1937)

In order to make the central span of the bridge shorter, and thus lighter, more stable, and less expensive, Chief Engineer Joseph Strauss proposed placing the south tower 340 meters into the strait. There were numerous unprecedented engineering challenges associated with construction in the roughly 25 meter deep water in the Golden Gate, but the most lasting controversy concerned the quality of the bedrock into which the piers would be built. The bedrock at the south pier is comprised of serpentinite. Serpentinite was known then to crumble to dust when weathered. Bolstering the lay-geologists intuitive concern about this material underlying the bridge, one of the foremost geologists of the early 20th century voiced vigorous reservations about that bedrock.

About Serpentinite

Serpentinite is metamorphic rock primarily comprised of serpentine, which forms from olivine metamorphosed by hot water. This tends to occur at seafloor spreading centers. Serpentine has relatively low density and often rises to accrete at the surface. (Wiese) It can be turned by exposure to the elements into an astoundingly weak stone which can be broken up and crushed by hand.

Serpentinite is not a very common surface rock – less than 1% of the Earth's surface is Olivine or Serpentinite. It does, however, serve as the bedrock along the south Golden Gate Strait. "At Fort Point, [the serpentinite] consists of two gently east-dipping sheets at least 50 meters thick…. The serpentine sheets consist of rounded blocks of massive bastite-bearing serpentine sheathed in intensely sheared serpentine." (Wahrhaftig, "39)

There are a few counter-claims to the general consensus that serpentinite is a dreadful foundation. Serpentinite is not always weak – when kept dry, it can be a hard stone. The New York City Department of Buildings considers Serpentinite a class 1b Medium-Hard foundation bedrock, with an allowable bearing pressure of 40 tons per square foot - the second highest classification. (NYC-DOB, Table 1804.1)
"Serpentine, contrary to popular belief, is not especially prone to landsliding everywhere, because the large serpentine body of Potrero Hill is almost completely free of landslides." (Schlocker, 86)

That said, serpentinite is notorious for its poor quality as a foundation:

"Serpentine being recognized as an unsatisfactory and occasionally unacceptable foundation material. In fact, rock engineering literature warns the engineer: *'Dams should not be placed on serpentinite"* and that the material is *"...unusable and unsuitable as the foundation for a dam.'"* (Glawe & Upreti)

"The south pier stands on serpentinite, a notoriously weak and slippery rock - no cause for confidence." (Alt & Hyndman, 141)

Ultimately, what becomes clear is that Serpentinite can vary in its characteristics: In an article comparing two large projects on serpentinite, Glawe and Upreti wrote: "[Some] serpentinite can be extremely closely fractured, with chlorite and talc infillings. The serpentinite exhibits a flaky and cataclastic rock texture… and could be easily excavated with a pick and the remaining small blocks… could be disintegrated by hand to sandy gravel size." This could also describe the serpentinite atop Land's End, as demonstrated to our Geology 21 class.

Glawe and Upreti continue: "Why did the serpentinite of the Kusan-3 dam site exhibit higher strength than reported elsewhere for serpentinite? ….Varying high strength values for serpentinite may result from differences in localized lithologic factors, micro and macro structures, mineralogical compositions and variations of interlocking of smaller grains….
If kept dry, Serpentinite can – as the continued existence of the septuagenarian Golden Gate Bridge attests – be a firm foundation stone. In 1934, this was not certain.

"Stop! Serpentinite!" Says Sensationalist Stanford Sage

Bailey Willis was trained as a mechanical and civil engineer in the 1870's. He worked as an engineer and geologist for railroads and joined the U.S. Geological Survey in 1884. His contributions to structural geology – regarding the formation the Appalachian Mountains in particular, led him to broad renown in geology circles. His subsequent travels and leading work in China advanced the understanding of Chinese geology and paleontology considerably. By the late 1890's, he was Chief Geologist of the U.S. Geological Survey. In addition to his scholarly works, he wrote popular books about his travels to China and Argentina. He became head of the Stanford Department of Geology in 1915. He retired as a professor in 1922, but remained actively involved with civil engineering and geology in California. He worked on municipal water supplies, earthquake preparation, and, in the 1920's, became a critic of the engineering of the Golden Gate Bridge. (Blackwelder)

Willis conducted a years-long campaign to defeat the effort to fund and construct the Golden Gate Bridge at its eventual location. He first wrote privately to Lawson, whom he'd known for years, and Strauss. At the height of his campaign, Willis wrote a two-full-newspaper-page letter published in a San Francisco weekly – *The* Argonaut in mid-September, 1934. Willis wrote, among other things

> "The southern anchorage and the south pier are founded upon a mass of sheared rock involved in a system of minor faults and consequently unstable to a degree likely to endanger the structure. The rock is serpentine and is subject to landslides, as may be seen in the immediate vicinity. Slides have occurred under natural conditions. the probability of their occurrence has been increased by blasting and would be gravely augmented by the weight of the structure it is proposed to erect on the foundation of the south pier. Such a slide would, to a greater or less extend, block the entrance to San Francisco harbor, change the tidal prism, and consequently the level of the tides, and would seriously affect the future of the city as well as cause the loss of the bridge."
>
> Bailey Willis, quoted in the Chief Engineer's Report of 1937.

This public airing of Willis's concern, along with his request that work be halted immediately and the bridge reengineered to have a pier drilled 250 feet into the bedrock, instead of 20 feet, was unsurprisingly not welcomed by the bridge design team. Chief Geologist Andrew Lawson charged Willis with being a professional alarmist." (Dvorak)

Willis was very dramatic, saying the south pier was positioned "on a 'pudding stone' of serpentine." He wrote "even vibrations from the San Andreas Fault might cause the pier site and its 200,000 pound load to slide into the channel." He added that in a large, 1906-sized earthquake, the weight of the bridge would cause the base of the serpentine to shear, and the whole bridge would collapse into the strait. (Dvorak)

Willis was not the only credible opponent to the location of the bridge. Engineers J.B. Pope, W.J.H. Fogelstrom, and Professor Charles Wing testified in court that "U.S. Coast and Geodetic Survey reports ***proved*** that the rock formations under the proposed south pier could not withstand the load…" and that costs would be quadruple Strauss's estimate. They were "establishment engineers… with strong local reputations. (Starr, p66)

Bridge Geologist Lawson himself wrote in 1930 – before Willis's efforts gained wide notoriety - that the south pier of the bridge would "have to be designed to depend upon the dead load rather than upon the tensile strength of the rock."

Ultimately, Willis's concerns were vigorously rejected by the engineering team, and his competence was questioned – noting the 50+ years since his earning an engineering degree, and his lack of professional experience as an engineer. His concerns were also rebutted with condescension in the Chief Engineer's Report of 1937, published in direct, if delayed response to Willis's public pronouncements.

"Bunkum!" Bellows Better Berkeley Brain

Andrew Lawson was, by the 1930's the preeminent geologist in the country. He had authored *the* definitive geological report on the 1906 earthquake, discovered and defined the extent of the San Andreas Fault, and been instrumental in identifying the Franciscan Complex.

In the early 1930's, when questions began to arise concerning the placement of the pier for the planned bridge, the Chief Engineer hired Lawson to investigate and ultimate support the location of the bridge. Lawson directed borings into the depths of the piers.

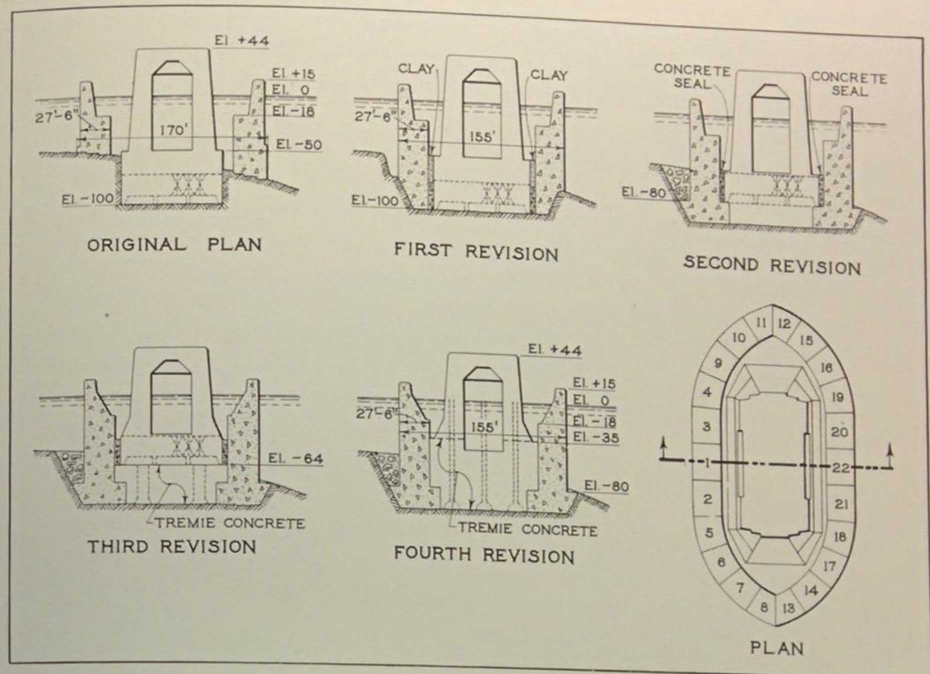
In contrast to Willis's press-friendly protestations, Lawson was predisposed to use carefully chosen phrases which were prone to misinterpretation by the general public. "Lawson required some coaching… to express his findings as strongly as possible, without academic qualification." (Starr, 94).

Lawson was noted as having described Willis's criticisms of the Bridge locale as "a fine example of a boogy-boo dragged in by the ears from the recesses of a vivid imagination to scare people. The astonishing thing about his present attack upon the stability of the Golden Gate Bridge is that he should have restrained himself so long."

How the Pier Was Built

Building an enormous concrete foundation for a bridge in 60-80' deep water with fog, shipping, tides and storms was something that had never been done before. There were many innovations in material science, mathematical modeling and general bridge design which were scaled up and put into practice for the Golden Gate Bridge.

First, a temporary bridge was built from Fort Point to the pier location. A large elliptical dam was built - a concrete bathtub the size of a football field (300' by 155'), and extending far higher than the mean surface level of the strait. This was necessary because the tide through the Golden Gate is disruptively forceful: up to 65000 metric tons per second, with the water moving at up to 10 km/h one way then the other. Those tides routinely fill the water with blinding silt, and can toss boulders most vigorously. (Starr, 96)
A caisson – a building designed to be sunk to facilitate construction underwater - was built in a nearby drydock and floated into place before the cofferdam was completed. The caisson was a very complicated construction in its own right. It had air locks, cage elevators, airtight refuge chambers and more. This caisson took over a year to build. Once the caisson was in place, but before the cofferdam could be completed around it, a storm blew in, severely damaged the caisson, and threatened to damage the cofferdam and undo a year's work. With more winter storms coming, the engineers decided to just pump all the water out of the cofferdam, and work without a caisson at all.



San Francisco Pier and Fender. Diagram shows original plan and subsequent progressive development during construction

The fender wall has been completed and the tremie seal is being poured

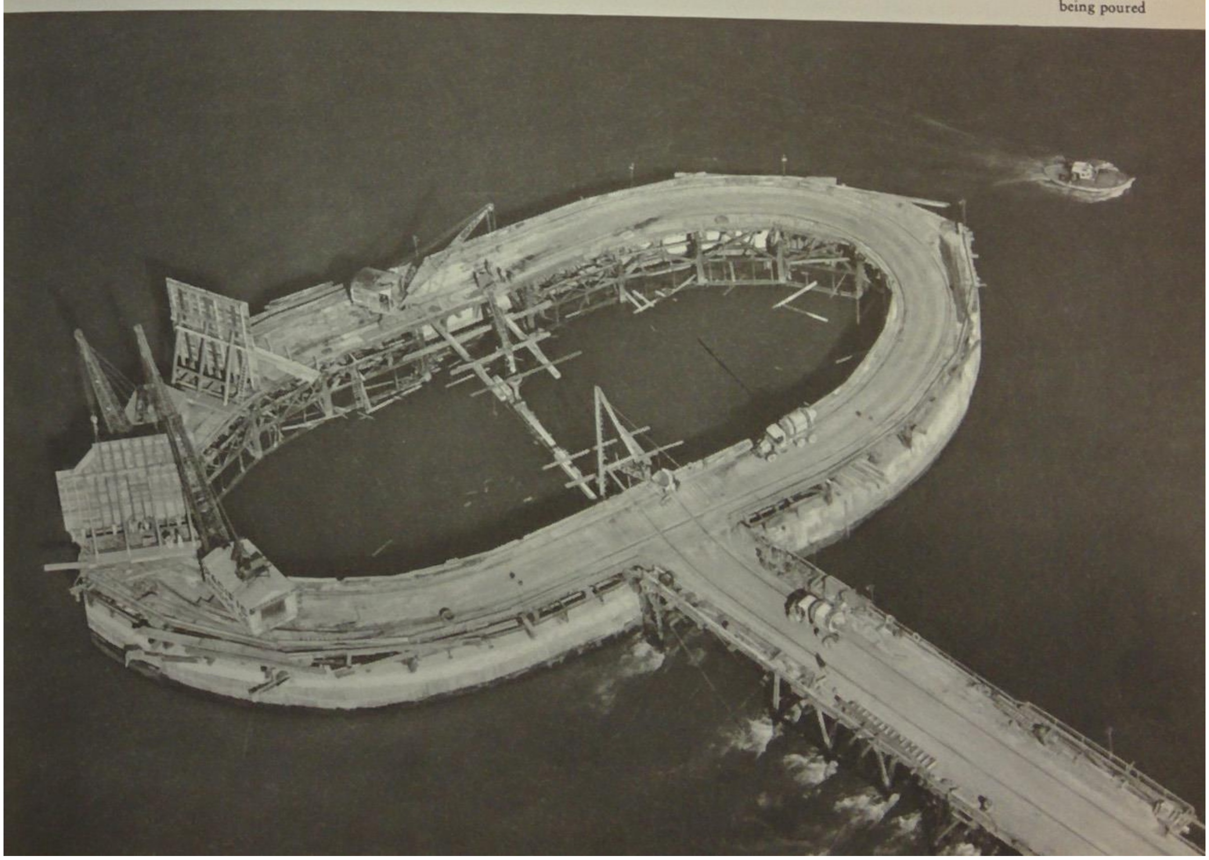
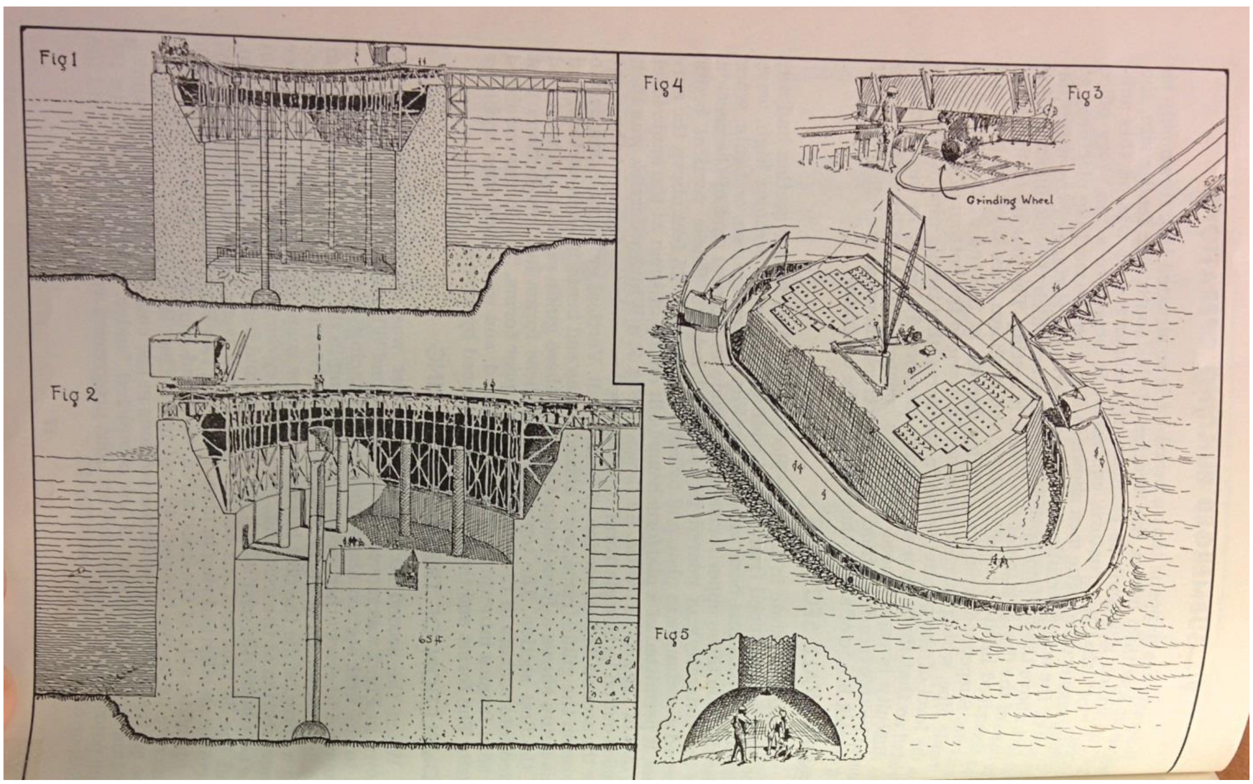


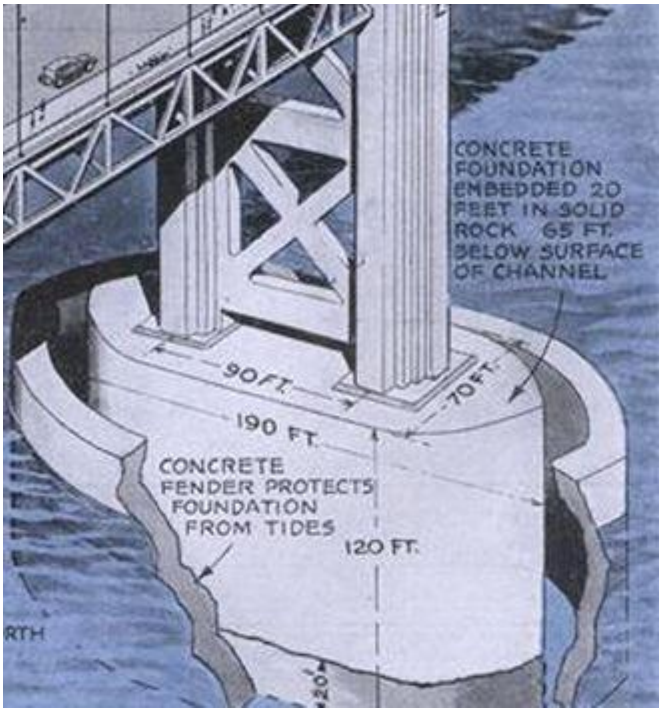
Photo Credit: E.C. Mensch, 1935

When the cofferdam was complete, the bay water was pumped out, so the silt at the bottom of the bay could be removed. The suspect serpentinite was exposed. Deep holes were drilled into the serpentinite, and Lawson determined that this was unusually solid, unfractured serpentinite. Still, the construction team had to excavate twice as deep as Lawson had originally estimated… but only one fifth as deep as Willis requested, to reach stone of sufficient quality to support the weight of the bridge. “In December 1934… Lawson descended into an inspection well over 100 feet beneath the sea surface and reported that "the rock of the entire area is compact, strong serpentine remarkably free from seams . . . when struck with a hammer, it rings like steel." The fender used to prepare the south tower foundation now serves to protect the pier from stray, fog-bound ships.” (Dvorak)



The inspection wells (figure 5) were 15’ diameter bells at the bottom of 4’ diameter holes drilled deep into the serpentinite. (E.C. Mensch, Ch. 7)

The concrete pier (illustrated below) was built of steel-reinforced concrete was built after the serpentinite bedrock had been excavated 15 meters below top of the serpentinite layer.



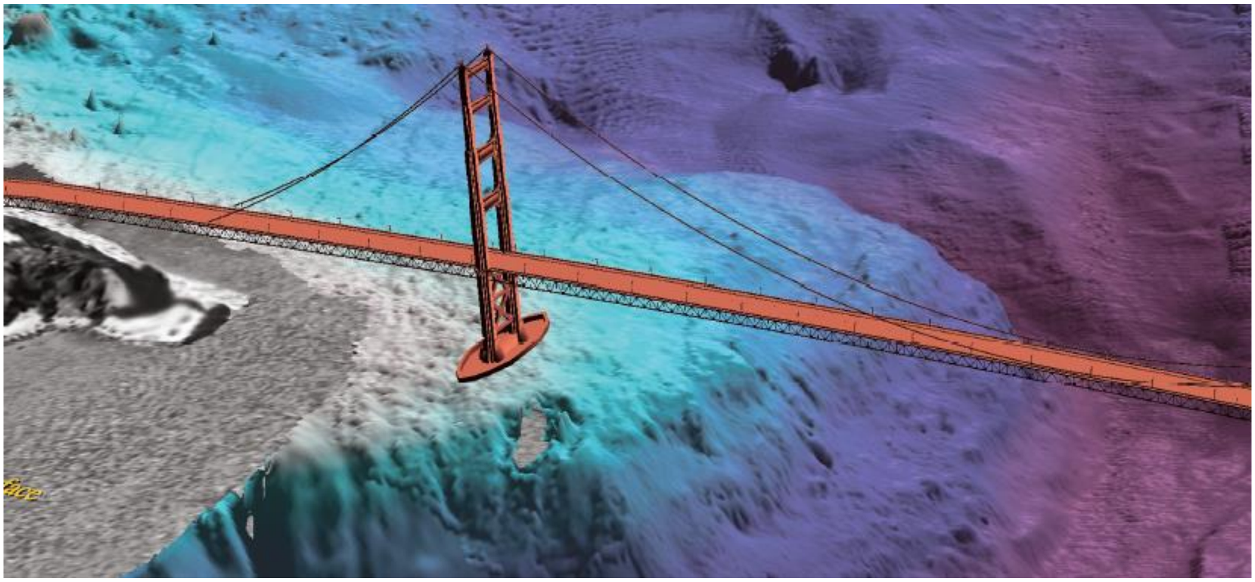
(Illustration: Popular Science, Mar 1931, p24)
Note that this drawing, which predated construction of the bridge by several years, does not reflect the additional depth excavated for additional support. The south pier extends about fifteen meters (instead of six) below the bay floor.

This greatest challenge met, the Golden Gate Bridge was ultimately constructed under budget, with a largely laudable safety record. That it still stands at 77 years of age is fairly good evidence the pier is not as doomed as Professor Willis thought.

Some thoughts on why this might be:
Willis's initial complaints about the bridge were written in 1927, in response to an early design by Joseph Strauss "which depended on the brute strength of rigid steel beams and thousands of tons of unyielding structure.". That design was subsequently abandoned in favor of a lighter, more flexible design conceived by Leon Moisseiff (Johnson & Leon) and calculated by a team led by Charles Alton Ellis, who authored the standard text on the mechanics and mathematics of framed structures. (Starr, 88). Ellis spent 20 months mathematically testing the bridge design. His conclusions were that it would be sufficient to withstand the tides, the winds, earthquakes, traffic, and its own weight. (Strauss, Appendix A) Note that Ellis is not credited here, though he was chiefly responsible for the calculations (Starr, 100)

As compelling as the Willis-as-Cassandra narrative is, warning an oblivious public of disaster in vain – Willis's arguments were quite aggressively and thoroughly discredited in the Chief Engineer's report. It should be noted that a copy of *The Argonaut* with Willis's polemic could not be acquired in time for publication. The Golden Gate Bridge District has done a fine job preserving the counter-argument.

Appendix I: 2006 Topography of the Golden Gate Strait under the South Tower of the bridge.



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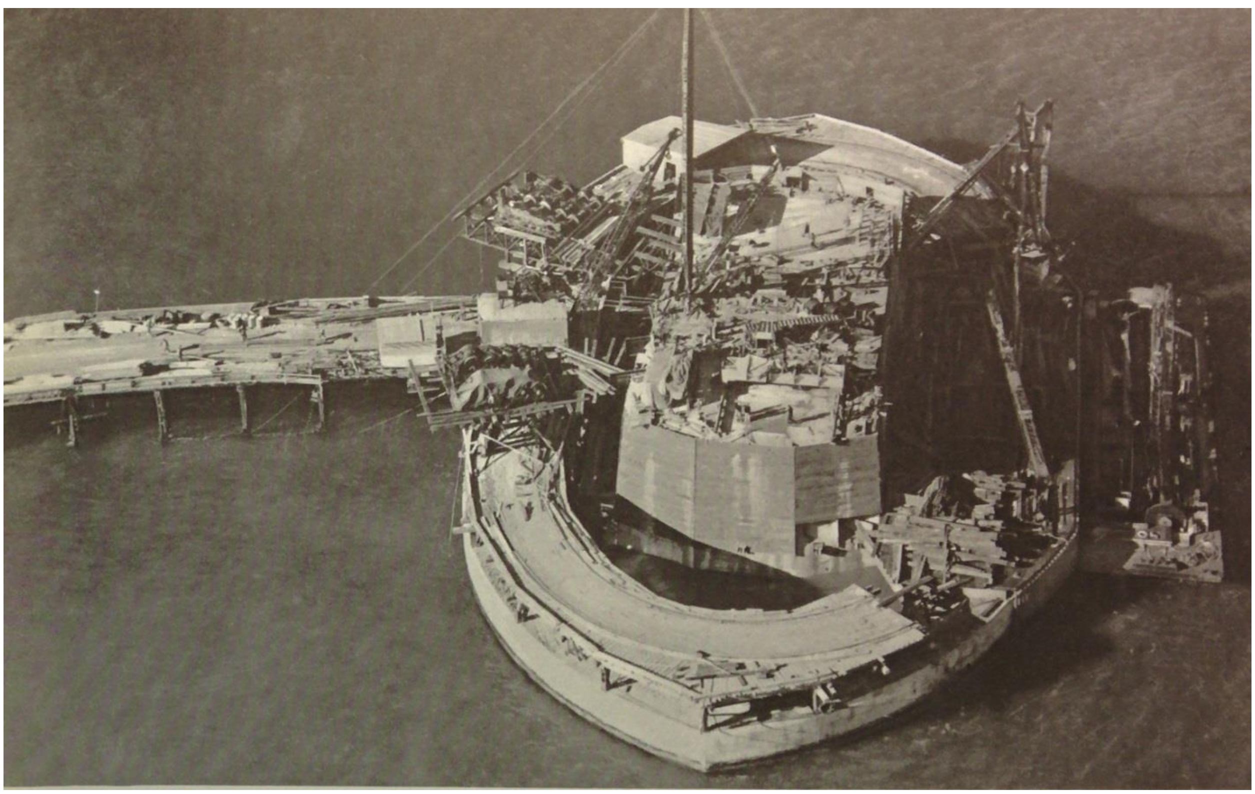

The pier going up, almost ready for the steel towers to begin construction, 1935. (Mensch)

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(it should be noted that many of these sources contributed only a page or two, and others were duplicative in their material.)

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