ASEE AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Paper ID #36103

The Engineering Design Process: The example of the Rio-Antirrio Bridge

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A Case Study in Engineering Design: The Rio-Antirrio Bridge

Preparing Future Engineers by Studying Past Projects

Basile Panoutsopoulos

Overtime Engineers have been recognized as problem solvers. For an Engineer to either reach a solution of a new problem or improve the existing solution of a previous problem follows several steps that form the Engineering Method. The Engineering Method is well established process, and the process is followed universally in the process' basic steps although sub-steps can vary due to the peculiarity of the original problem. A very common occurrence is that while trying to solve a problem a previously hidden sub-problem is discovered, then Engineers go back to make modifications on the specifications or change the design process based on what Engineers have learned, with this portion of the Engineering Process being repeated as many times as necessary. This is known as iteration and was a common phenomenon in the designing and building process of the bridge.

The Rio-Antirrio Bridge was proposed in 1880 by then Prime minister of Greece Harilaos Trikoupis (The official name of the bridge is "Harilaos Trikoupis bridge") but the idea was abandoned due to technological shortcomings and exorbitant cost. The idea resurfaced in 1998 and was completed in 2004 just in time for the 2004 Olympic Games taking place in their birth country, Greece. The Bridge has been designed and constructed to cope with the exceptionally difficult physical conditions in the straits between Rion and Antirrion, the Gulf of Corinth: high water depth; deep strata of weak soil; very strong seismic activity; strong winds; and fault displacements. For these reasons, quite innovative techniques needed to be developed, such as improving the strength of the in-situ soil by means of inclusions and suspending the bridge deck on its full length to be as isolated as possible. The National Geographic Rio-Antirion Bridge in Greece (https://www.youtube.com/watch?v=dmwIjpjcPv0&ab_channel=EllinikoMeli) documents the effort. This paper proposes the preparation of future engineers through the study of previous projects. It will be beneficial to the reader to watch the video before reading this paper and again during the reading.

Introduction

Charilaos Trikoupis (July 11, 1832 – March 30, 1896) was a 19th-century politician who served also as a prime minister of Greece. During his tenure he proposed two major technical projects: The construction of the Corinth Canal and a bridge to connect the cities of Rio and Antirrio across the Gulf of Corinth. The technical infrastructure was needed to support the economy, and to attract foreign investment to a developing country of the time. The Corinth Canal was initially proposed in classical times [1], which connects the Gulf of Corinth in the Ionian Sea with the Saronic Gulf in the Aegean Sea was recommenced in 1881 and it was completed in 1893. [2].

The other proposed project, the Rion-Antirio Bridge was beyond the technical and financial abilities of the state. Construction and completion of the bridge would not happen for more than a century after the project was initially proposed. The bridge, officially named the Charilaos Trikoupis Bridge in his honour, was completed in 2004. The bridge dramatically improves access to and from the Peloponnese, which could previously be reached only by ferry or via the Corinth canal in the east. This bridge is widely considered [3] to be an engineering masterpiece. The site of the bridge is difficult, requiring solutions to each of the various problems encountered to be very innovative. These problems include span of the bridge, deep water, unstable materials for foundations, seismic activity, the probability of tsunamis, and the expansion of the Gulf of Corinth due to plate tectonics.

Figure 1. Map of the relative location of the bridge at the Canal of Corinth and the Rio-Antirrio bridge.

The transportation between the cities of Rion in Peloponnese and Antirion from the mainland of Greece was done by ferry boat taking about forty-five minutes. Using the bridge, the crossing time was reduced to approximately five minutes.

Table 1: Location of the Rion-Antirion bridge. [4]

Official name	Charilaos Trikoupis Bridge
Owner:	Government of Greece
Coordinates:	38°19′17″N 21°46′22″E
Carries:	Ionia Odos
Crosses:	Gulf of Corinth
Locale:	Rio, Greece Antirrio, Greece
Maintained by:	Gefyra SA

Table 2: Characteristics of the Rion-Antirion bridge. [4]

Design	Cable-stayed bridge by Berdj Mikaelian
Total length	2,880 meters (9,450 ft)
Width	27.2 meters (89 ft)
Hight:	170 m above the water.
Longest span	560 meters (1,840 ft)
European roads:	The bridge is part of the Ionian Road (A5) that connects to European Road (E55). It connects western Greece with main Europe.
Construction:	French group Vinci SA which includes the Greek companies: Hellenic Technodomiki-TEV, J&P-Avax, Athena, Proodeftiki, and Pantechniki.
Cost:	The total cost: €630 million,[4] Other sources talk about €839 million.[5]

The Engineering Method

The method or process of orderly steps used by engineers to solve a problem and complete the solution up to the final product is called "Engineering Method". The solution of a problem can that of a new and never attacked before problem; the solution of a solved problem under the lights of a new science and technology, materials, funding, etc.; or the optimization of the solution of a previously solved problem based on availability of new computer tools. The nature of the problem and the proposed solution dictate the exact steps followed but the general process can be illustrated in Figure 1.

The defining characteristic of the Engineering Design Method is the iterative process by which Engineers arrive at the final solution to the problem under consideration. A common occurrence in the design process is to arrive in new problems during the solution. This includes unforeseen situations and failed testing. In this case the engineers need to return to the previous steps and reevaluate and modify the selected approach for one or more steps or provide a totally new approach to reach the solution altogether. To which step or steps will return, depends on the nature of the problem. The Engineering Method is like Solving problems at school but more involved. While the school problems are simple and have typically one solution, the practical problems have many solutions from which one must be selected.

Typical Steps of the Engineering Design Process [5], [6]

1. Definition of the problem: This is a very important step; the given and the requested quantities must be identified accurately. The constraints under which the solution must be sought must be stated.
2. Research on previous work: History of the problem and attempted solutions. The success or not of previous solutions is important to understand the nature of the problem.
3. Brainstorming, Requirements, Possible Solutions, Selection of Feasible and Optimum Solution. The rejection and selection of solutions is a team discussion and conclusion.

4. Implementation of Selected Solution, address unforeseen problems, Revisit and Modify Existing Solution. While the process in going on new problems appear that must be solved. Accidents happening must be corrected.
5. Partial Compliance with Requirements., Identify Possible Causes, Unforeseen New Problems. When testing, observations, measurements establish noncompliance the causes must identified and corrected. This includes return to previous steps, a characteristic of the Engineering Design Method.
6. Present Final Product, Celebrative Festivities, Documentation. In addition to public acceptance of the completed project. The project must be finally documented and maintenance of its for its projected life must be established.

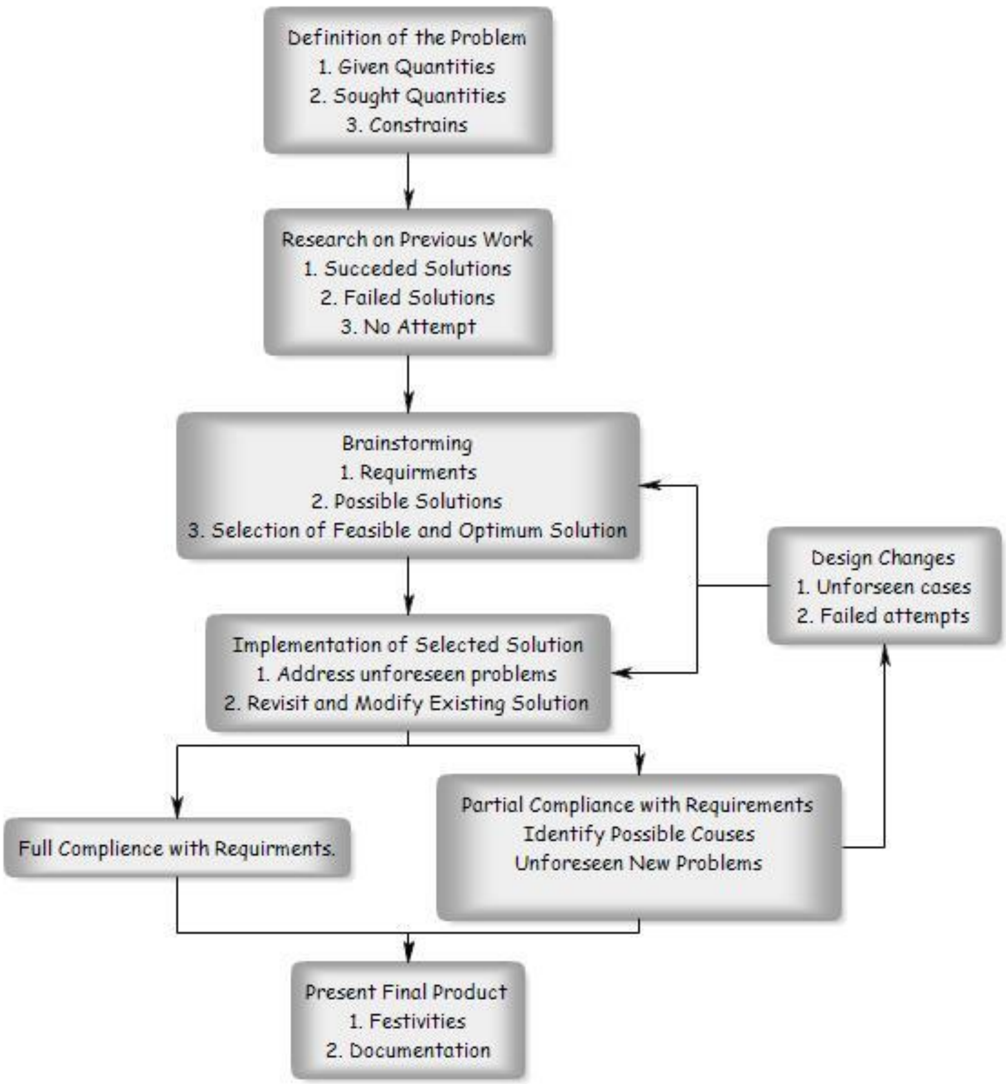

Figure 2: Typical steps of the Engineering Design process.

The Rio-Antirrio Bridge and the Engineering Design Process

Due to the unusual conditions of the straits where the bridge is to be located, several unique engineering problems needed to be solved. The approach used is that of a top-down design, the bridge problem is divided in smaller problems, [7].

The Problem: Create a bridge to connect the two sides of land considering that the water depth reaches 65 m, the seabed is mostly of loose sediment, the seismic activity is considerable, and possibility of tectonic movement is significant; the Gulf of Corinth is expanding at a rate of about 30 mm a year. In addition, the hills on either side create a wind tunnel where 70 mph winds are common.

The length of the bridge is 2,380-metre (7,808 ft-approximately 1.8 miles). The bridge has two vehicle lanes per direction, an emergency lane, and a pedestrian walkway. The width of the bridge is 28 m (92 ft). The bridge has five span four-pylon cable-stayed portion of length 2,252 m (7,388 ft). The Rio – Antirion Bridge deck might be considered the longest cable-stayed "suspended" deck in the world.

Fig. 3. The finished Rio-Antirrio Bridge. [8]

Brainstorming - Selection of Beam Type: There are four types of bridges: Beam, Arch, Suspension. and Cable state. The main criterion for the selection of the bridge type is its length - 1.3 miles. The evaluation of each type brings conclusion of acceptance or rejection. The Beam type are the longest bridges around the word. The hundreds of supports needed will block the ship travel. Unacceptable. The Arch type can stay clear for big ships. The span will require a bridge four times longer than any bridge build before. The risk is too great. Rejected. The Suspension type requires enormous cables from one shore to another. It is expensive. Billions of Euros. Unrealistic. This leaves the Cable stayed. A cable-stayed bridge has one or more towers (or pylons), from which cables support the bridge deck. The weight of the deck is supported by several nearly straight diagonal cables in tension running directly to one or more vertical towers. The towers transfer the cable forces to the foundations through vertical compression. The tensile forces in the cables put the deck into horizontal compression. But it will be the first bridge to overcome the conditions of the place.

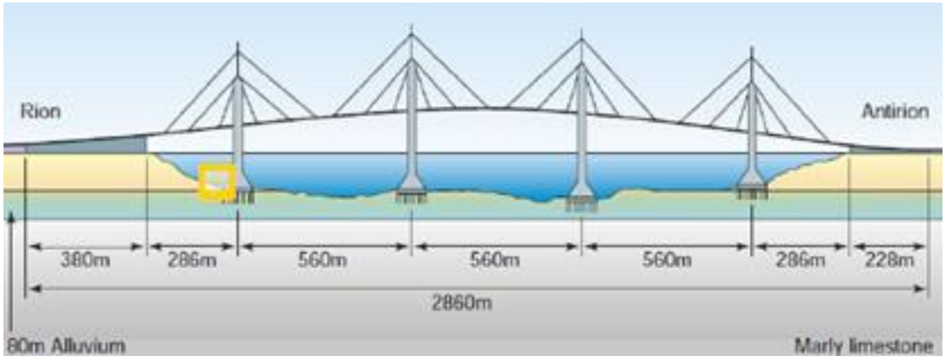

Figure 4. Elevation chart of the bridge. [9]

Problems, Proposed, and Implemented Solution.

Foundation of the bridge: The seabed of the location of the bridge is about 65 m deep. The seabed is sand and silt for hundreds of meters down. Bridges need a solid base to sit on, typically bedrock. Furthermore, the earthquakes of the area cause liquefications (Stable soil to behave as liquid).

The Engineering solution was to make a rocky bed. The foundation was transformed to a semi-solid. The wet sand was stabilized by installing 200 metal piles in the sand underneath three out of four piers. The pipes were hollow steel and were inserted vertically into the ground. On top of the stabilized wed sand gravel meticulously leveled to an even surface was deposited. This is a difficult endeavor at this depth. The pier footings were rest on the bed of gravel.

Movement of piers due to earthquakes: Motion of the piers on the ground can cause them to tip over and take the bridge down.

The piers are sitting on top of gravel. The gravel is on top of the metal pipes that were inserted to stabilize the soil. The piers would have room to move laterally around and slide on top of the gravel near the sea floor in case of an earthquake. The gravel bed will absorb the mechanical energy transforming it to heat.

Keeping the Bridge deck stable while the piers move: On top of the is located the deck. Earthquakes will force the piers to move but the deck needs to state relatively stable.

The engineering solution was to separate the deck and the pier. They will move independently. The bridge decking is literally hanging from the piers. An earthquake will shake the piers and will swing back and forth the decking.

The proposed solution created another problem. The swing of the deck can be large enough, in case of a big earthquake, that will hit the pier’s arms.

The engineering solution was to use a viscous damper. It turns the kinetic energy of the deck movement into heat. It slows movement and prevent the bridge from self-destruction.

The bridge decking is connected to the pylons using jacks and dampers to absorb movement; too rigid a connection would cause the bridge structure to fail in the event of an earthquake and too much lateral leeway would damage the piers.

For these reasons, quite innovative techniques needed to be developed, such as improving the strength of the in-situ soil by means of inclusions and suspending the bridge deck on its full length to be as isolated as possible, [10].

Widening of the strait due to plate tectonics: There is also provision for the gradual widening of the strait over the lifetime of the bridge.

The Engineering Solution: The inclusion of expansion joints in the bridge which gives the bridge the ability to expand up to five meters laterally.

Vortex shedding: The gale-force winds lead to vortex shedding or swirls of air around the cables that may cause severe oscillating vibrations that travel throughout the structure. This operating condition of the cables leads to metal fatigue that can cause the bridge decking to collapse.

The Engineering Solution was to install a helical strake, a metal coil that acts like a metal spring winding its way to the top. When winds pass across the helical strakes, the vortices break apart evening out over the length of the cable, preventing vortex shedding which prevents the cable from snapping due to excessive vibrations and keeping the cable safe, [11].

The Gulf of Corinth, the winds, and the naturally occurring wind tunnel of the Corinthian Gulf: The strong winds of the Gulf of Corinth could cause the bridge to wing continuously.

The Engineering Solution: Protection from the effect of high winds on the decking is provided using aerodynamic spoiler-like fairing and on the cables using spiral Scruton strakes.

The Engineering solution to keep the bridge deck from moving except in case of an earthquake was to add a fuse attached to the pistons under the bridge. The high winds will keep the bridge deck steady and only when the movement is high as in the case on an earthquake, the fuse will fail, and the viscus dampers will move to protect the bridge decking by converting the kinetic energy of the swinging bridge into thermal energy caused by the viscous fluid resisting the swaying of the bridge, [11].

Inauguration:

The bridge was inaugurated on 7 August 2004, a week before the opening of the 2004 Summer Olympics in Athens. Olympic torchbearers were the first to officially cross it. Otto Rehhagel, the German football coach who won the Euro 2004 Championships for Greece and Costas Laliotis, the former Minister of Public Works during whose term the project had begun were among them.

Maintenance – Longevity - Serviceability:

A structural health monitoring system was installed during construction on the bridge. Still operating, it provides a 24/7 surveillance of the structure. The system has more than 100 sensors, including:[13]. The bridge needs non-stop serviceability, [13], [14]. The monitoring of the state of the bridge includes various sensors and instruments.

- 3D accelerometers on the deck, pylons, stay cables, and on the ground to characterize wind movements and seismic tremors.
- Strain gauges and load cells on the stay cables and their gussets
- Displacement sensors on the expansion joints to measure the thermal expansion of the deck.
- Water-level sensors on the pylon bases to detect infiltration.
- Temperature sensors in the deck to detect freezing conditions.
- Linear variable differential transducer (LVDT) sensors on the stay cables to measure movement.
- Load cells on the restrainers for recalibration in the event of an earthquake
- Two weather stations to measure wind intensity, direction, air temperature, and relative humidity.

One specific element of the system is the ability to detect and specifically treat earthquake events. The Department of Geology at the nearby to Rio University of Patras, monitors the earthquake activity especially in the region of modern Greece. The Laboratory is part on a wider National and International network.

Awards to the Bridge

The technical innovations that have been employed for the realization of this project are manifested by their numerous references in the scientific and technical literature. The Rion-Antirion Bridge has been awarded nine international awards by the international scientific community. The following are a few: The 2006 Outstanding Structure Award from the International Association for Bridge and Structural Engineering, the 2006 episode of Megastructures on the National Geographic Channel [15], the 2011 the episode of Richard Hammond's Engineering Connections [16], and the 2015 episode of the Science Channel series Impossible Engineering [17].

Educational Use:

The subject of this paper may be used as a case study in a course or certification program on “Bridges” [18]. Students can address the problem, identify it, and propose possible solutions. The technological tools evolve. An alternative “better” solution may be proposed or investigated.

Conclusion

The Rio-Antirrio bridge is a world marvel of engineering. The solution of a problem “Build the Bridge” to connect two opposite parts of land separated by the sea required the creation of new solutions. A characteristic of the solution process was that during the implementation new problems appeared that required solution. To the solution of the new problems, the constrains of the location and conditions on the bridge’s location must be added. At the end the “Engineering Design Method” was the tool used to solve an engineering problem. To fully appreciate it one must watch the fifty minutes long video or other related videos. The bridge was finished four months ahead of schedule. The bridge operates continuously since 2004.

Acknowledgements:

The author would like to thank Theodore Panoutsopoulos, a recent civil engineer, for the various discussions and help into some technical points.

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