THE RIO ABAJO FOOTBRIDGE: PROMOTING DEVELOPMENT THROUGH THE USE OF RESILIENT INFRASTRUCTURE

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ABSTRACT

In the remote farmlands of the developing world, walking is the primary form of transportation. When rivers flood during the rainy season, walks to school, work or the doctor can become life threatening without a bridge to cross. For hundreds of millions of people worldwide, rural isolation caused by a shortage of safe river crossings is a significant impediment to economic development and self-sufficiency. Non-profit organization Bridges to Prosperity (B2P) works with vulnerable communities to build footbridges that create year-round access to essential services. Data describing flood and wind events is often not available in the rural areas of the developing world where the footbridges are constructed. Resilience is an important aspect of the footbridges' design and construction, as the bridges must provide access to essential services after flood or wind events. This paper presents a case study of an 81-metre pedestrian suspension bridge constructed in Nicaragua in March 2015 as part of a B2P build project with the community of Rio Abajo and bridge professionals from Canada and the United States. Ensuring resilience to floods, windstorms and vandalism was the basis for several design decisions and construction procedures implemented on the bridge. Structural redundancy ensures resilience if bridge components are removed or damaged. Foundation locations and design assumptions ensure the structure will continue to fulfill its intended function during significant flood events. Less than one year after construction, the structure performed as intended when the Pueblo Nuevo River flooded its banks.

Keywords: footbridge, international development, bridge construction

1. PROJECT DESCRIPTION

The World Bank estimates that one billion people in the developing world suffer from rural isolation. The Rural Access Index (RAI) was developed by the World Bank to evaluate the percentage of a rural population that lives within two kilometres of an all-weather road. Nicaragua has an RAI of 28%, meaning that of the country’s 2.3 million rural residents, only 655,000 live within two kilometres of an all-weather road (Roberts et al., 2006). Residents without all-weather road access are often at a disadvantage compared to those with all-weather road access because healthcare, education and economic opportunities are often not accessible year-round.

The Rio Abajo pedestrian suspension bridge in northern Nicaragua spans 81 metres over the Pueblo Nuevo River. It was built in 2015 to replace a previous bridge that was destroyed by Hurricane Mitch in 1998. The 2,000-person community of Rio Abajo uses the footbridge to access essential services in the nearby town of Pueblo Nuevo. During the rainy season when floodwaters make the river crossing dangerous, Rio Abajo residents previously had to swim across to Pueblo Nuevo, or alternatively walk nine kilometres east to the town of Condega.

The bridge was constructed as part of a bridge building program by Bridges to Prosperity, a United States-based non-profit organization that works with local governments, corporate partners, and student groups to construct footbridges with isolated communities around the world. The project team also included the municipality of Pueblo Nuevo, local volunteers from the community of Rio Abajo, and corporate partners COWI North America and Kiewit Bridge & Marine. The bridge is supported on cast-in-place concrete foundations and anchors.
Pedestrians access the bridge through cast-in-place concrete access ramps at each abutment and cross the river on a one-metre wide walking surface constructed from wood planks. Loads from the walking surface are transferred to the main cables through 10-millimetre diameter steel bar hangers which are connected to double angle steel floor beams spaced one metre apart. The main cables each comprise three 15-millimetre diameter post-tensioning strands. 9-metre tall steel pipe towers, which are braced to each other in the transverse direction, carry the superstructure loads to the tower foundation. A partial elevation view of the bridge is shown in Figure 1.

![Figure 1: Rio Abajo footbridge partial elevation](image)

The Rio Abajo bridge was designed by staff engineers at B2P based on one of two standard designs that the organization employs on nearly all of its bridges. The corporate partners reviewed the design to gain familiarity with the bridge and create construction procedures. B2P staff worked with volunteers from Rio Abajo to construct the cable anchorages, tower foundations and access ramps. Subsequently, a team of twelve North American bridge designers and constructors travelled to Rio Abajo for two weeks to help the Rio Abajo community volunteers and Bridges to Prosperity staff build the bridge superstructure. Superstructure construction was completed in eight construction days without the use of cranes or mechanical work platforms.

### 2. RESILIENCE CONSIDERATIONS FOR BRIDGES

Resilience is defined as the ability to recover from or adjust easily to misfortune or change. In the structural engineering community, resilience refers to a structure's ability to adjust to a disturbance and remain in service. The most common disturbances to structures include flood and wind events. North American bridge design codes include provisions for dealing with these disturbances. When designing and constructing bridges in developing countries, however, these code provisions are difficult to apply, and more detailed work must often be completed to ensure that bridges are resilient.

#### 2.1 Resilience Considerations in Developed Countries

The Canadian Highway Bridge Design Code (CHBDC), which is also applicable for the design of pedestrian bridges, includes provisions for the design of structures to resist flood and wind events. Bridges must be able to withstand a normal design flood, which has a 50-year return period, without any structural damage to the bridge or approach structures. Bridges are also designed to accommodate a check flood, which is a flood with a return period at least twice the normal flood, without loss of structural integrity or failure of the approach embankments. For the design flood and the check flood, the flood discharge and high water level are used to determine the structure's vulnerability to flooding. The CHBDC requires that field surveys that quantify the site's hydraulic and geotechnical characteristics, flood history and land use trends be carried out as part of the design process. In addition, an estimation of a bridge's vulnerability to scour is required based on inputs such as the maximum water level and maximum water velocity (Canadian Standards Association, 2014).
The CHBDC includes provisions for the design of structures to resist wind. The design wind speed is based on a return period of 100 years for bridges with spans greater than 125 m and 50 years for other bridges. Hourly mean reference wind pressures are tabulated for the design return periods based on the bridge location. An equivalent static wind load for design is generated using the design wind speed with modifications for site topography, height of the bridge above ground level and sensitivity of the bridge to dynamic wind action. To determine the force effects due to wind, the static wind load is applied in the transverse, longitudinal and vertical directions in various combinations for differing angles of attack (Canadian Standards Association, 2014).

2.2 Resilience Considerations in Developing Countries

In developing countries where B2P typically constructs footbridges, effects of flood and wind events are much more difficult to quantify than in developed countries, but structural resilience is equally important. This uncertainty means that code procedures used in North America, such as those in the CHBDC, cannot be readily applied and extra work must often be completed to ensure that the structures can withstand floods and wind. Factors that contribute to the difficulty in providing appropriate structural resilience include:

1. It is difficult to obtain data describing flood events, such as maximum flood discharges, high water levels and a site's flood history.
2. Reference wind speeds and wind pressures for varying return periods are not readily available.
3. Structural properties, including material resistances of steel and concrete, and geotechnical properties are more uncertain due to a lower degree of quality control and lack of site investigation equipment. For example, cast-in-place concrete may have a compressive strength as low as 10 MPa.
4. Uncertain maintenance and inspection schedules increase the probability of member failure.

Determining the effect of flood and wind events on footbridges in developing countries must be completed in spite of the difficulties associated with this exercise. For many communities, the footbridges provide the only means of access to health care and government services in nearby towns. After flood and wind events, these footbridges must provide access to essential services in nearby communities.

When designing footbridges in developing countries, the need for structural resilience must be balanced with the need for structural efficiency. Infrastructure budgets in developing countries are typically much smaller than in North America. This means that as the cost of bridge construction increases, fewer bridges can be built. In order to reduce rural isolation for the most people possible, excessive conservatism that ensures resilience is not the preferred option, as it limits the number of bridges that can be built. On the other hand, unresilient structures do not perform as intended during flood and wind events and have an increased life cycle cost due to the need for repairs and possible premature replacement. Therefore, a balance between efficiency and resilience is required.

3. RESILIENCE OF THE RIO ABAJO FOOTBRIDGE

The Rio Abajo footbridge design is based on one of two standard designs that B2P uses for all its bridges, with modifications to suit the bridge site. The standard design is resilient without being overpriced and inefficient. The bridge is designed to resist flood and wind events. Resilience to flooding is particularly important because the bridge provides the only means of crossing the Pueblo Nuevo River when the water level is high. Details of the standard suspension bridge design are available in the B2P Bridge Builder Manual (Bridges to Prosperity, 2013).

3.1 Resilience to Floods

The Rio Abajo footbridge design considered flooding of the Pueblo Nuevo River. During the initial site survey, the river profile was surveyed and the high water level determined by observing the flood marks along the riverbanks and asking local residents for the highest water level that they remembered. This method approximately estimates the highest water level that has occurred in the last 25 years. The tower foundations were set back 6 metres from the river edge at the high water level and the bottom of the foundation was set 1 metre below the top of grade. The minimum freeboard of the bridge when fully loaded with dead and live load was set to 3 metres above the high water level. The setback and foundation depth provide a buffer for the bridge foundations.
to protect them from potential scour at high water levels and the freeboard clearance allows room for floating debris to pass under the bridge during a flood.

Considerations for flooding of the Pueblo Nuevo River governed the design of the bridge anchors. The deadman anchors, shown in elevation in Figure 2, resist horizontal sliding and vertical uplift forces that are transferred into the anchor from the main cable through the transition block and transition arm. The anchors resist the horizontal sliding force by mobilizing the passive resistance of the soil ahead of the deadman anchor block. During the anchor design, the soil ahead of the anchor block was assumed to be fully saturated for the calculation of the resistance of the anchor against sliding, as would be the case during a flood event. Similarly, the weight of the soil and anchor block used buoyant unit weights from a fully saturated condition when determining their resistance to vertical uplift. This prevents a high water table or flood from compromising the structural integrity of the bridge anchors.

![Figure 2: Rio Abajo footbridge anchor elevation](image)

In September 2015, less than one year after the bridge opened, the Rio Abajo region received a large downpour of rain. During this time, Rio Abajo residents observed that the water level had risen slightly above the high water level considered in the design of the bridge. The bridge functioned as intended during the flood, and no damage to the bridge was noted after the flood waters receded. This observation provides the designers with assurance that the bridge can function as intended during the floods that typically occur in Nicaragua’s rainy season. Figure 3, captured a few days after the September flood event, shows the Pueblo Nuevo River passing under the Rio Abajo footbridge. At the time of the picture, the water level was approximately one metre below the design high water level.
3.2 Resilience to Wind Events

Design of the Rio Abajo footbridge for wind events follows the standard design principles used on all B2P footbridges. The lateral wind load is referenced from footbridge design guidelines published by Swiss non-profit organization Helvetas based on their experience with footbridge building in Nepal. The guidelines assume a peak wind speed of 160 km/h acting laterally on the walkway and a wind coefficient of 1.30. For the Rio Abajo footbridge, which has a cross-section as shown in Figure 4, the lateral bridge area and solidity ratio of 20% result in a lateral wind design load of 40 kg/m. A 40 kg/m wind load was applied to the entire footbridge length in combination with full dead and live load to calculate force effects for a wind load combination.

ASCE 7-10 "Minimum Design Loads for Buildings and Other Structures" provides risk categories for various structure types. Category IV buildings and structures are defined as essential facilities, the failure of which could pose a substantial hazard to the community. Failure of the Rio Abajo footbridge would pose a substantial hazard.
to the community, especially after a significant windstorm when travel to clinics and hospitals may be required, so it can be classified as a Category IV structure. For Category IV buildings and structures, ASCE 7-10 recommends that the wind speed used to determine design wind loads be based on a 1700-year return period 3-second gust wind speed (American Society of Civil Engineers, 2010). Although ASCE 7-10 only includes wind speed maps for the United States, wind speed maps have been developed for the Caribbean and Central America. These wind speed maps show that the 1700-year return period 3-second gust wind speed is 150 km/h for regions around Rio Abajo, Nicaragua (Vickery & Wadhera, 2008). The 160 km/h wind speed used in the wind loading design calculation provides a slightly conservative estimate of the wind load that the footbridge could be subject to in a significant wind event. Footbridges in the developed world are generally not classified as Category IV structures, so the fact that the Rio Abajo footbridge design wind speed satisfies a Category IV requirement demonstrates the bridge's resilience to significant wind events.

The design approach used on the Rio Abajo footbridge is based on consideration of a static wind load. Many long span bridges, however, are also susceptible to the dynamic effects of wind. Helvetas footbridge design guidelines state that for footbridge spans of up to 120 m, dynamic effects due to wind load are not expected to be significant, and consideration of a static wind load is sufficient (Helvetas, 2003). Based on previous practical experience, Bridges to Prosperity typically installs lateral wind guys on footbridges with spans greater than 85 metres to limit dynamic wind effects. The installation of wind guys typically increases the cost of a bridge significantly as additional cables and foundations are required. As the Rio Abajo footbridge span is less than 85 metres, wind guys were not installed. If dynamic effects due to wind become problematic, wind guys could be post-installed to stiffen the bridge (Bridges to Prosperity, 2013).

4. RESILIENCE OF THE RIO ABAJO FOOTBRIDGE TO VANDALISM

In addition to resilience considerations for flood and wind events, design and construction of the Rio Abajo footbridge considered the effects of possible vandalism. B2P has found that a lack of availability of building materials in some areas of the world where footbridges are built can result in structural components being removed from the bridge to be used for other purposes. This issue was considered during the design of the footbridge and influenced several construction procedures.

In order to ensure that the Rio Abajo footbridge can continue to fulfill its intended function if some structural components are unexpectedly removed, key members were designed with structural redundancy. The walkway consists of floor beams and suspenders spaced at one metre, with deck planks spanning between them as shown in Figure 5. These components are typically most at risk of being removed from the bridge, as they are easily accessible. The deck planks are cut from *tempisque*, a local Nicaraguan hardwood, and are installed side-by-side to form the walking surface. In addition to uniformly distributed live load, the deck planks are designed for a 227-kilogram point load from a motorcycle or livestock hoof. If one or two deck planks are removed from the bridge, the others can continue to provide a means of crossing the bridge, as each plank acts independently to resist the applied pedestrian loads. The deck plank joints are staggered longitudinally so that if a cross beam or suspender is removed from the bridge, a minimum of two planks will span two metres to the next intact floor beam. Although the deck planks cannot resist a livestock or motorcycle point load when spanning two metres, bending stresses are acceptable for typical pedestrian loading in this scenario. The main suspension cables were also designed with redundancy in mind: each cable comprises three sheathed post-tensioning strands, designed to a factor of safety of three for axial loads. If one post-tensioning strand is removed or damaged, the other two can continue to support the bridge structure until the other is replaced or repaired.
Several construction procedures were implemented to make it more difficult to remove structural components from the Rio Abajo footbridge. The bolts connecting the deck planks to the floor beams were countersunk and the holes were filled with caulking to reduce the access to the bolt heads and prevent them from being taken out to remove deck planks. The threads on cable clamps connected to tieback cables at the anchors were deliberately worn down to prevent them from being removed. A concrete cap, shown in Figure 2, was cast on the end of the transition block to impede access to the main cable anchors.

Local volunteers played an important role in the construction of the Rio Abajo footbridge, and they will be responsible for the future bridge upkeep. Community volunteers constructed the bridge foundations with assistance from B2P staff and worked alongside the corporate partners to construct the superstructure, as shown in Figure 6. This allowed the volunteers to gain an understanding of the requirements for construction of suspension footbridges, and will allow them to recognize areas of the footbridge that need repair. Participation in the construction project also generated a sense of ownership of the bridge. These factors will help ensure that the footbridge will be repaired when required and will continue to provide the community of Rio Abajo with year-round access across the river.
5. CONCLUSIONS

The Rio Abajo footbridge provides the community of Rio Abajo with safe and reliable access to schools, healthcare, and markets in the nearby town of Pueblo Nuevo when high water levels in the Pueblo Nuevo River make the river crossing dangerous and impractical. The bridge functions as a lifeline route for Rio Abajo residents to access services in Pueblo Nuevo. Uncertainty regarding design loads for floods and wind events, site conditions, and inspection and maintenance schedules resulted in the implementation of several design and construction procedures that ensure resilience to floods, wind events, and removal of structural components. These procedures promote resilience without being overly conservative and dramatically increasing the cost of the bridge. Design assumptions and foundation layout provide structural resilience to flood events and scour. Design wind speeds equivalent to those for essential facilities ensure the bridge will remain in service after a windstorm. Consideration of structural redundancy and limiting access to critical components ensure removal of a component of the structure does not cause collapse. Together, these design considerations provide an efficient and resilient structure that will provide the community of Rio Abajo with access to essential services for years to come.

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