the rib-to-deck specimens with TEUs demonstrated higher fatigue strengths than those with CU.

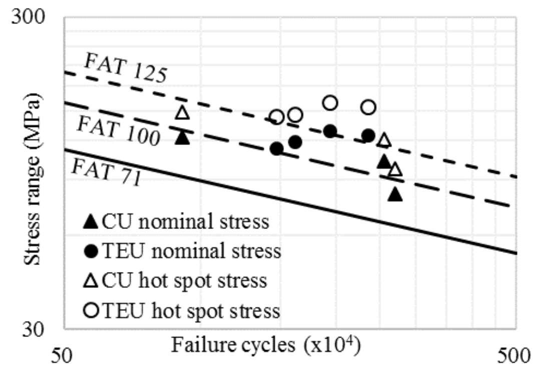

Fig. 7. S-N data of the specimens. Adapted from the work of Heng et al. (2017).

FATIGUE TEST OF FULL-SCALE OSD SPECIMENS

To verify the application of TEUs in field applications, full-scale fatigue tests of OSD specimens were carried out (Heng et al. 2017). Two full-size OSD specimens were fabricated with steel Q345qD (SAC 2015), including one using TEU and another using CU. In order to simulate the most critical situation for rib-to-deck joints, the ribs between outer webs of box girders were selected to simulate in the tests (Mukherjee and Roy 2015). The specimens were 6,200 mm long and 2,600 mm wide, consisting of an 18 mm-thick deck plate, four 8 mm-thick U-ribs and three equally spaced floor beams, shown in Fig. 8. Two T-shaped components were used to simulate the web and bottom flange of a box girder. The boundary condition of continuous beam was employed and simulated by the six hinge bearings installed on the bottom flange of the T-shaped components.

Two actuators were used to apply cyclic loadings to simulate the effect of passing vehicles. The two actuators worked in a phase difference of 180 degree to simulate the passing of heavy axles. As per infinite fatigue check in AASHTO specification (AASHTO 2012), 2.25 times the HS20 fatigue truck with an impact factor of 1.15 were used for the evaluation of rib-to-deck joints. In the study, an impact factor of 1.3 and a magnification factor of 1.5 was used to consider overloaded truck (Zhang et.al 2013). Thus, a load range of 320 kN was adopted in the beginning of tests.

The fatigue tests were performed in two steps. First, the specimen was loaded under the cyclic loads of 10 to 330 kN for 2 million cycles. Then, DP test was performed to examine the occurrence of fatigue cracks. If no crack was found in the rib-to-deck joints, the cyclic loads were increased to the range from 10 to 450 kN until any fatigue crack was observed in the rib-to-deck joints.

For both specimens, no fatigue crack was observed in the rib-to-deck joints in the first 2 million cycles. For the CU specimen, after the specimen was loaded for 4.19 million cycles, two fatigue cracks were observed at the weld toe of the rib-to-deck joints near the actuator #3. Fig. 9 shows the results of DP tests performed to visualize the cracks. For the TEU specimen, a total of 8.59 million cycles had been applied when the first fatigue crack was observed at the weld toe of the rib-to-deck joints near the actuator #3. Thus, in OSD specimens, the use of TEU significantly postponed the appearance of fatigue cracks and increased the fatigue life of the rib-to-deck joints by 105% (from 4.19 million to 8.59 million cycles).

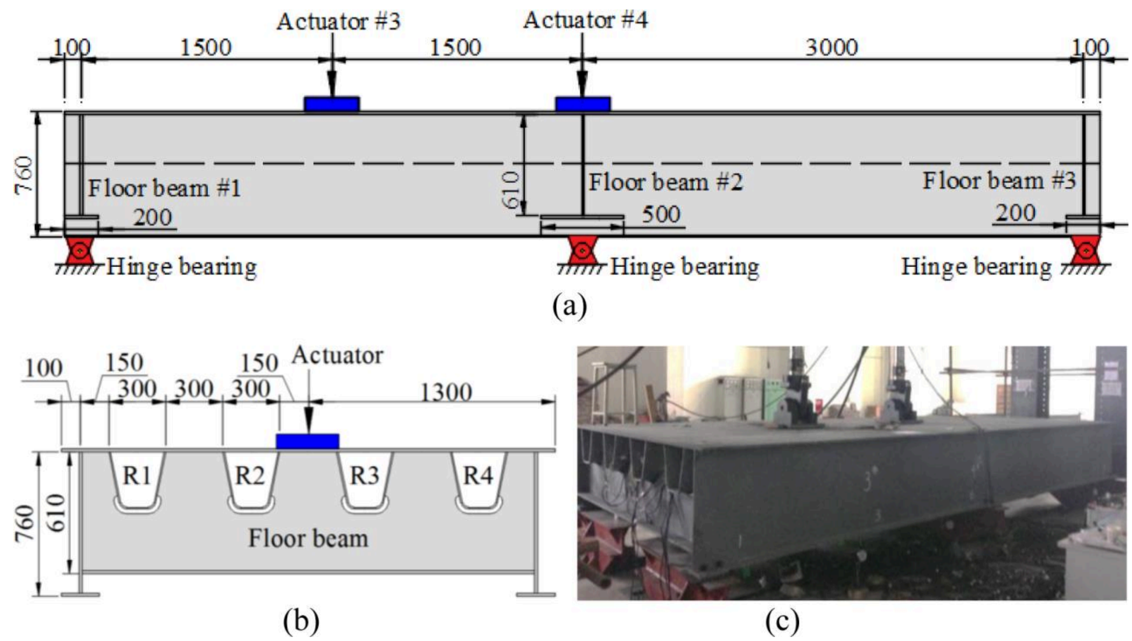

Figure 8. The full-scale OSD specimen: (a) elevation view; (b) sectional view; (c) photograph. Unit: mm. Adapted from the work of Heng et al. (2017).

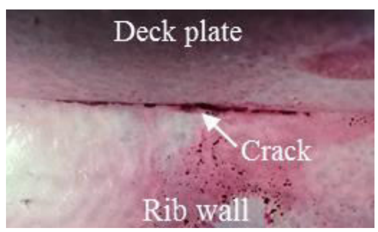

Figure 9. Typical crack at rib-to-deck joints in OSD specimens - taken by Heng.

APPLICATION IN ENGINEERING PRACTICES

As per the studies presented above, the fatigue strength of rib-to-deck joints could be effectively improved by using TEU, which could, in turn, improve their service life. The research results have been included in specification *Cold-formed U-Rib Steel Section for Steel Structure of Bridge*, authorized by Standardization Administration of China (SAC). Meanwhile, the TEU has also been used in engineering projects such as the New Sanyuan Bridge and the Fenghuangshan Viaduct, as shown in Fig. 10.

The old Sanyuan Bridge, a conventional RC bridge built in 1984, located at a crucial point in the urban transportation framework in Beijing. After more than 30 years' operation with extremely high traffic volume, the old RC bridge was too weak to maintain its serviceability and the reconstruction was carried out by the relevant departments. In the reconstruction, the OSD bridge was employed to finish the erection work in 43 hours. TEUs were used in the fabrication of the OSD, to improve the durability and reduce the maintenance costs of the bridge.

The Fenghuangshan Viaduct, built in Chengdu city, carried three lanes per bridge, including two fast lanes for light-weight passenger cars and a bus-only BRT lane. The bus traffic, which has high-volume and heavy-weight in Chengdu, imposed a great threat to the fatigue life of the rib-to-deck joints. To improve the fatigue performance, TEUs were used within the range of BRT lane.

(a) (b)

Figure 10. Application of TEUs in practice: (a) New Sanyuan Bridge in Beijing – taken by Zheng; (b) Fenghuangshan Viaduct in Chengdu – taken by Heng.

CONCLUSIONS

In this paper, the fatigue evaluation of rib-to-deck joints in orthotropic steel decks (OSDs) with thickened edge U-ribs (TEUs) was performed. The effectiveness of TEU over the conventional U-ribs (CU) was demonstrated with experiments on the specimens using TEU and CU. The results have been incorporated into the relative specification in China, and the TEU has been used in several engineering projects.

The main conclusions could be summarized as following:

(1) The average fatigue strength of TEU specimens was 20% higher than that of CU specimens in terms of the nominal stress range and 24% higher than that of CU specimens in terms of the hot spot stress range.

(2) In terms of the nominal stress range, all the four data points of the TEU specimens are above the FAT 100 curve, while only one of the three data points of the CU specimens is above the FAT 100 curve. The similar trend has also been found in terms of the hot spot stress range with respect to FAT 125 curve.

(3) Fatigue tests of two full-scale OSD specimens were carried out to test the feasibility and advantages of the TEU over the CU in field applications. The fatigue life of the rib-to-deck welded joints with TEU was increased by 105% (from 4.19 million to 8.59 million cycles), proving the effectiveness of TEUs in enhancing the fatigue resistance of the rib-to-deck welded joints.

(4) Based on the research result, the TEU has been used in engineering projects such as the New Sanyuan Bridge and the Fenghuangshan Viaduct, to improve the fatigue performance of rib-to-deck joints in OSDs.

ACKNOWLEDGEMENT

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Repairing the Yullajung Pedestrian Suspension Bridge: Service Learning in the Nepal Himalaya

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ABSTRACT

The paper describes how a severely damaged pedestrian suspension bridge located in a remote valley in the Nepal Himalaya was strengthened by repurposing the existing main cables and anchorages to support expected pedestrian and yak loads. A repair scheme was designed and implemented over a seven day period during a service learning trip in the summer of 2016. The strengthened bridge functions as a cable-stayed bridge without compressing the deck. Surveying showed that the main cable tensioning operation raised the deck three inches at midspan which reduced loads on the abutment anchor bolts. Any additional live loading would go directly into the modified structural system and not overload the deck or bolts.

YULLAJUNG BRIDGE DESCRIPTION

The Yullajung pedestrian bridge crosses the Bhote Koshi River in the Thame Valley of the Nepal Himalaya (see Figure 1 and Figure 2). The bridge is 55-foot-long and six feet wide and is the primary access route to the community of Yullajung in Sagarmatha (Mount Everest) National Park. The bridge was built in the late 1980s after the previous bridge was washed out by a historic flood. This remote Sherpa village resides at an elevation of 12,500 feet and is accessed by way of a 24 mile hike from the local airport at Lukla (elevation 9380 feet). There are no roads in this region of Nepal so vehicular transportation is not possible. This bridge is very important to the Yullajung community because it provides access to medical services, schools, monasteries, neighboring communities and the market in Namche Bazar.

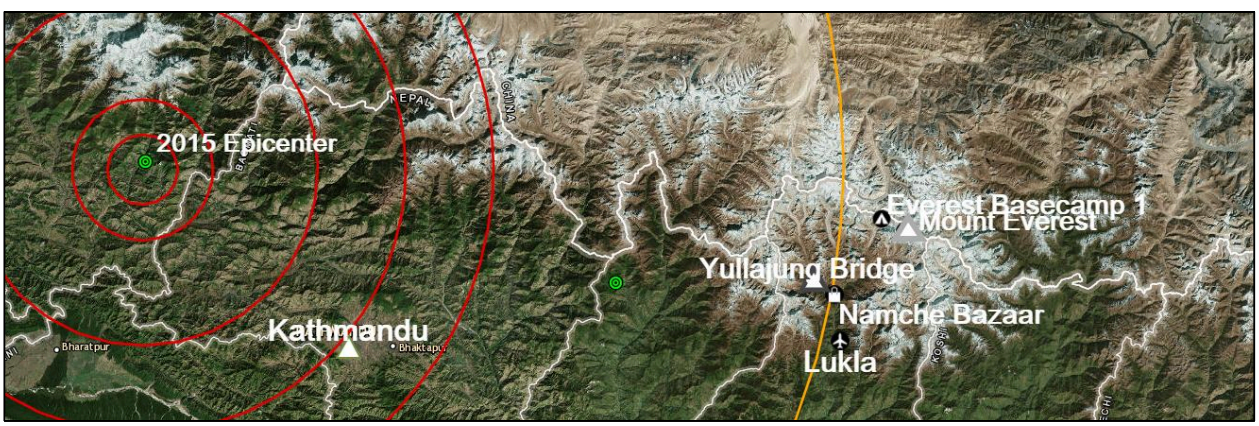

Figure 1 Bridge location with respect to 2015 earthquake epicenters, Mount Everest, and Lukla Airport.

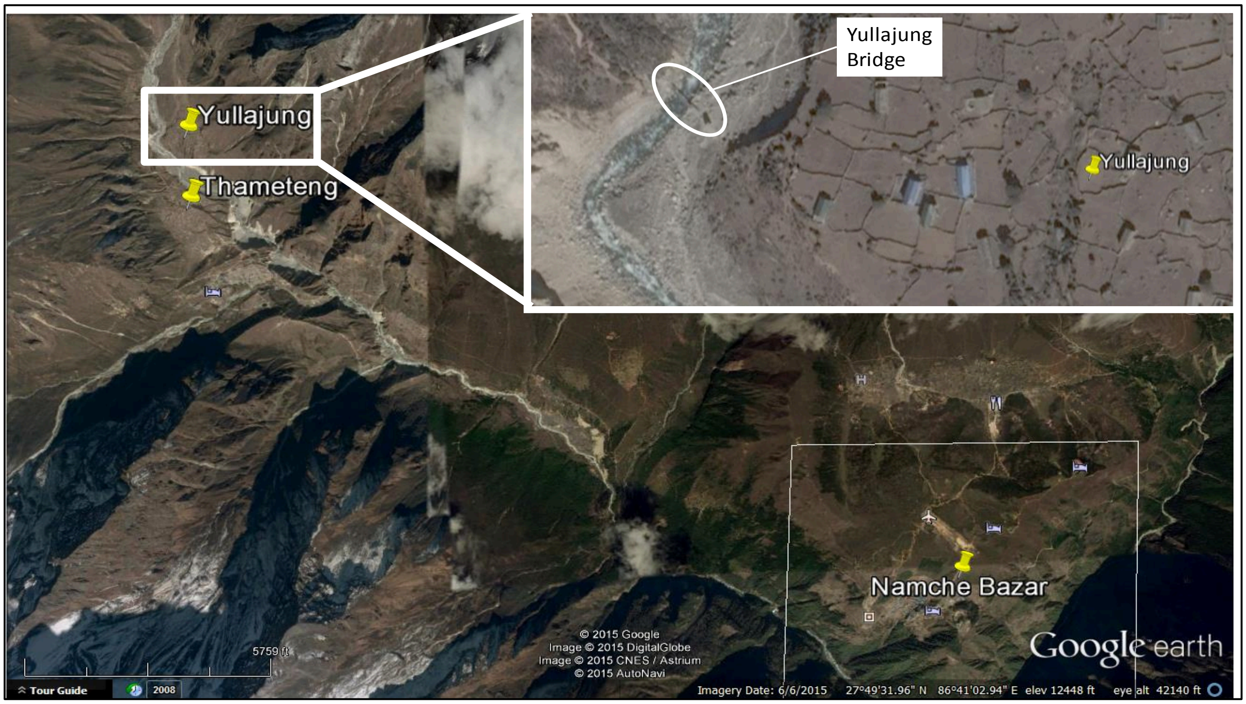

Figure 2 Google Map of Thame Valley, including Thameteng, Yullajung and the Yullajung Bridge (inset)

The original configuration was a suspension bridge with a single unreinforced stone tower on the Yullajung side of the river (see Figure 3). The anchorage on the Thameteng side of the river is at the top of an adjacent hill. The bridge deck consists of two channels with a steel plate bolted to the top flange. Each channel is attached to the abutments with four 7/8” diameter anchor bolts. Vertical hanger rods connect the deck to the main cables.

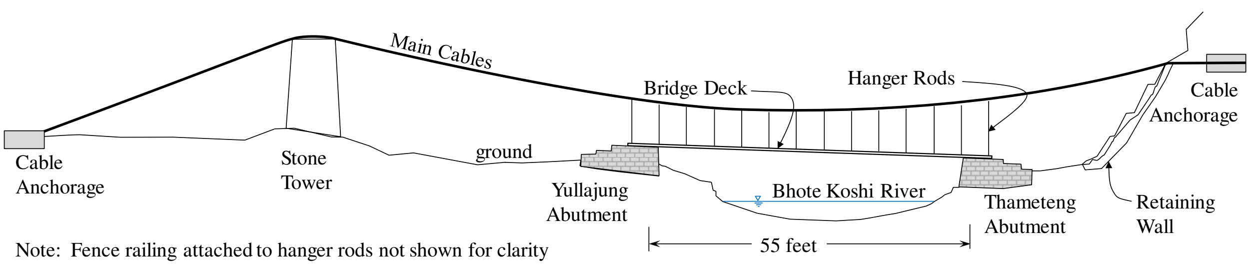

Figure 3 Schematic of original bridge configuration. (Note: Not to scale)

DAMAGE FROM THE GORKHA EARTHQUAKE

The 2015 Gorkha earthquakes destroyed the stone suspension tower and completely detensioned the main suspension cables (see Figure 4). Lack of support from the main cables resulted in an eighteen inch sag at the midspan of the deck and a structure that functioned as a stress ribbon bridge rather than as a suspension bridge (see Figure 5a). Eight anchor bolts connected the steel deck to the abutments and prevented complete collapse of the bridge (see Figure 5b). This bridge has been scheduled for replacement in 2018 by the Nepal Trail Bridge Program, however the community has little choice but to continue to use it, as their alternatives are to either walk an additional 3-4 hours to the next river crossing or to use the old trail across active landslides.

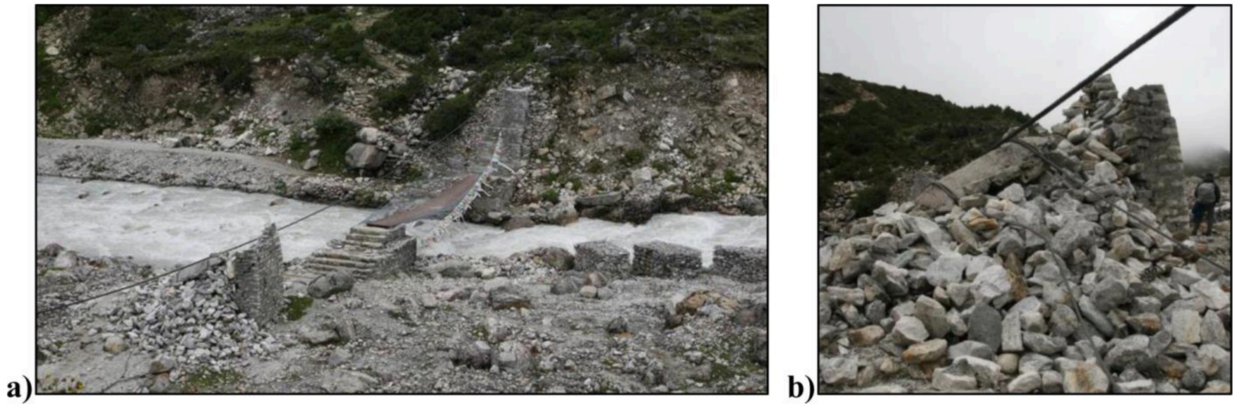

Figure 4 a) Overview of bridge site from the Yullajung side of the river. Note the riprap protection on the right of the photo which protects against erosion and scour of the Yullajung abutment. b) Remains of the Tower on the Yullajung side of the river. Note the water pipe on the top right and the cable saddle at the top of the rubble pile.

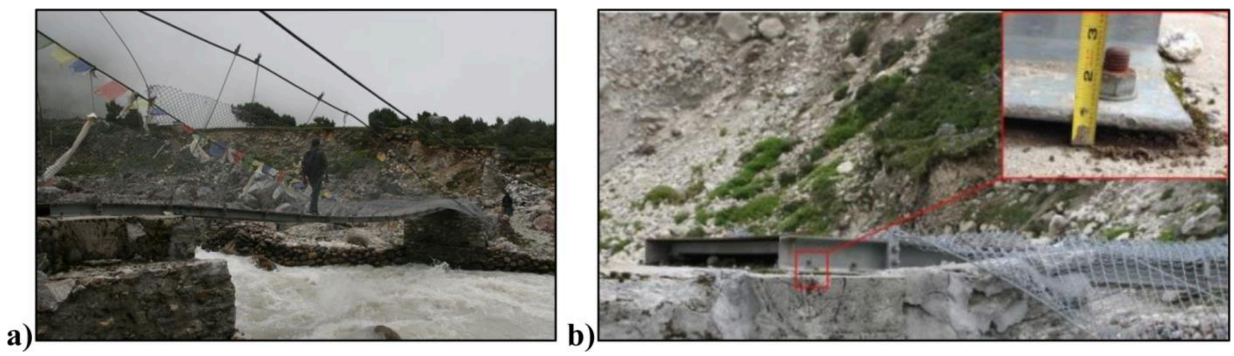

Figure 5 a) Elevation view of the bridge from the Thameteng side of the river. Note the bending of the bridge deck. b) Thameteng abutment. Note the four anchor bolts on each channel and the gap between the anchor plate and the abutment which indicates the anchor bolts are beginning to pull out of the abutment.

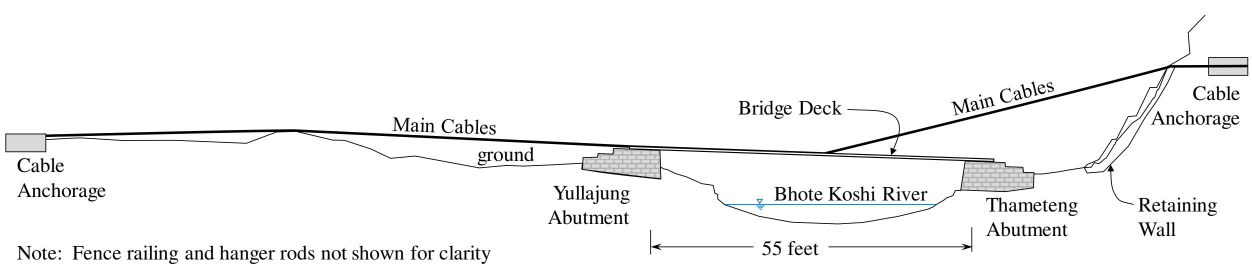

Figure 6 Schematic of strengthened bridge configuration. (Note: Not to scale)

DESIGN CRITERIA AND REPAIR CONCEPT

Upon inspection of the current condition of the bridge and consultation with community members to understand their concerns and wishes, our team decided on the following design criteria.

- Strengthen the bridge to last approximately three to five years until a replacement can be designed and constructed.

- Utilize existing material as much as possible.
- Minimize maintenance requirements.
- Ensure the bridge can support loading from pedestrians, livestock, snow, and yak trains weighed down with mountaineering equipment. Yak loading provided the governing load case.
- Grade 36 steel for the hanger rods. This was determined based on field measurements using elementary mechanics principles and a luggage scale.
- Repairs must be accomplished using available hand tools (i.e. pocket knives, multi-tools and few hand wrenches).
- Only make changes that improve the bridge
- Design concept must allow structural analysis calculations to be conducted by hand due to lack of relevant computer software at the site

a) b)

Figure 7 a) Clearing away the tower stones and releasing the main cables from the Yullajung anchorage b) Positioning large stones with the assistance of the Nepal Army.

Our team considered several possible strengthening concepts, including a traditional asymmetric cable-stay configuration, but decided that the most feasible concept was a modified cable-stayed bridge layout. This strengthening concept repurposed the existing main suspension cables and threads them through the hanger rod–to-deck padeye connections and attaches the main cable to the existing undamaged Yullajung anchorage (see Figure 6). The benefits of this concept are that it utilizes numerous undamaged portions of the bridge (i.e. main cables, cable anchorages and deck connections), provides uplift forces at the midspan of the bridge, and eliminates compression loading in the bridge deck. It was important in the modification of the bridge to not induce axial load in the deck (cable-stayed bridges typically do result in large deck compression from the horizontal components of the diagonal cable forces) due to significant permanent vertical deformation of the deck, even after modification, possibly resulting in global buckling of the structure. As a suspension bridge, the original structure carried no compression loading in the deck, and it was critical that any modifications to the structure not make the bridge worse. Due to the stiffness of a cable-stayed system, any additional live load on the bridge is supported directly by the modified structure and does not overload the deck and its abutment details. Our team presented this repair concept to community leaders for their input and approval. Community leaders then discussed the proposed repairs with the community, and our team received approval to implement the repairs the following day with the full support of the community.

Figure 8 a) Threading the main cables through the hanger padeye loops at the deck b) Pulling the main cables through the hanger padeye loops.

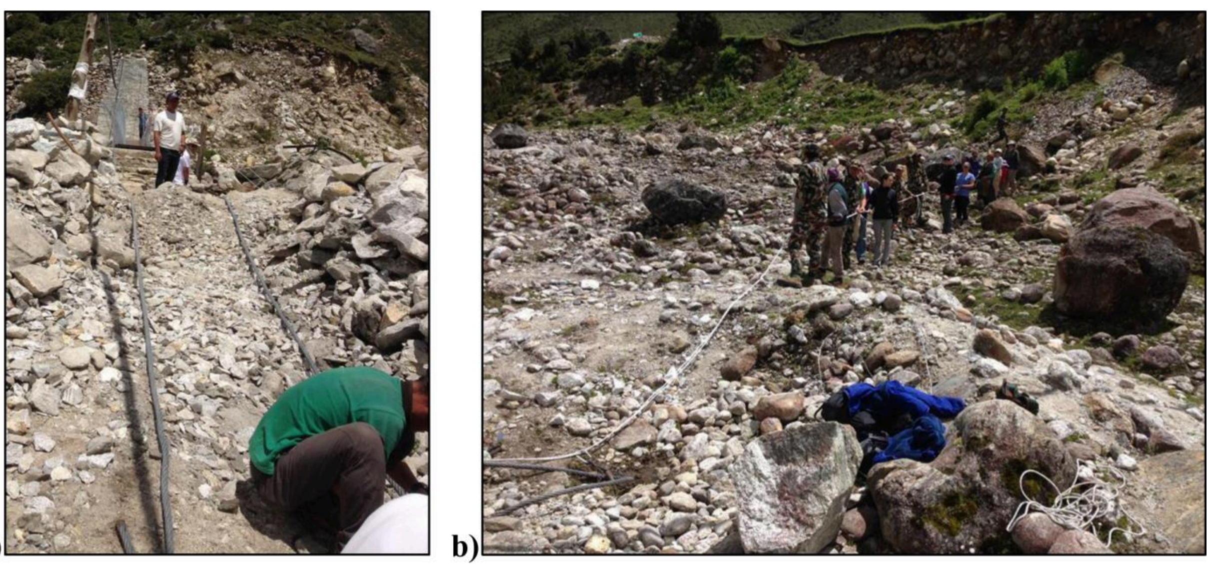

Figure 9 a) View of main cable alignment from Yullajung anchorage. b) Preparing to hand tighten a main cable.

CONSTRUCTION

Construction of the approved repair concept occurred over the course of three days and included assistance from all available community members, as well as soldiers from the nearby Nepal army outpost. Construction occurred in nine stages as follows.