INVESTIGATION OF THE CONSTRUCTION OF A 19TH CENTURY WOODEN FLUME SUSPENDED ON A CLIFF

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The Hanging Flume near Uravan, Colorado, U.S.A., is an engineered structure from a brief but important period in the development of the American West. Constructed during the 1880s for hydraulic mining of gold, the ditch and wooden flume extended approximately 20 kilometers, at times suspended up to 75 meters above the Dolores and San Miguel Rivers on the face of a sandstone cliff, all for the purpose of transporting water. Preserving this innovative construction technology and documenting its place in the development of gold mining the U.S. is challenging. A team of archaeologists, engineers, industrial rope climbers, a wood scientist, a geologist and historians participated in preliminary documentation of the site. Unless remaining sections of the Hanging Flume are documented and stabilized while they are relatively intact, this unique structure will continue to deteriorate until evidence of its innovative building technique and details of its construction are lost forever. This presentation will discuss the use of industrial rope climbers and video equipment suspended from above to assess the condition and construction methodology of the Hanging Flume.

KEYWORDS: FLUME, HYDRAULIC MINING, GOLD MINING, BRACKET FLUME, HANGING FLUME

1. BACKGROUND

Within the spectacular Dolores River Canyon in Colorado are remnants of the Hanging Flume (the Flume), constructed by the Montrose Placer Mining Company in the 1880s to mine gold from placer deposits along the river. The Hanging Flume was an engineering marvel for its time. The scale is difficult to comprehend due to the size of the site, especially when seem from one of several vantage points along its length (Figure 1). What remains along the Dolores River Canyon is still spectacular. Although some segments of the Flume are relatively intact, close examination reveals that much of the wood has been lost to scavenging, vandalism or deterioration (Figure 2).

Figure 1. View of the Hanging Flume above the Dolores River. The arrow points to only one of the Flume segments which can be seen in this photo.

Figure 2. Section of the Flume showing deteriorated condition in 2002 (near location of arrow in Figure 1).

2. CONSTRUCTION HISTORY

A plan to extract fine gold from placer deposits along the Dolores River led to the construction of the Hanging Flume, beginning in 1887 and taking three years to complete. Hydraulic mining, which had been in use in California since the 1850s, was a profitable means of removing gold from placer deposits. Wooden flumes were an efficient way of transporting water for hydraulic mining operations.

Hydraulic mining uses use water to separate gold particles from the lighter-weight minerals found in placer deposits. Hydraulic mining channels water under pre-determined volumes and pressures, controlled by the size of the flume and the rate of elevation drop (grade) between a headgate and a pressure box. Along the way the water is moved through whatever economical means are available.

Earthen ditches and wooden flumes transport water across relatively flat land. Where hanging flumes were built, the land was not flat. At elevated areas above a river, trestles or hanging flumes were constructed to maintain the necessary drop in grade to provide the desired volume and pressure. Trestle bents support the flume from below, where a relatively horizontal ground surface was available near the desired elevation. Brackets were used along the more or less vertical cliff face, where a trestle would have been impractically tall. Because both trestles and brackets support the flume box at roughly 8-foot intervals, both are called “bents” in this report.

The technique for hanging a flume on the side of a cliff was developed in California. Called a bracket flume, or hanging flume, construction was quite dangerous and required precision work to maintain the grade. Most notable of the bracket flumes was the Miocene Flume in California (Figure 3). Designs varied but were remarkably consistent, probably due to the limited number of engineers and builders familiar with their construction. No as-built drawings of the Hanging Flume are known to exist. Along its length, the structure is intermittently ditch, wooden flume and hanging flume.

The Hanging Flume began at a headgate on a log and cable dam on the San Miguel River above the town of Uravan. There is no remaining evidence of the location or construction of the headgate. From the headgate, water was transported in a ditch adjacent to the river through an area that later developed into the town of Uravan. The ditch was, at some points, supported by stone walls. While evidence of the location of the ditch exists, it has long since filled in with debris.

Eighteen trails were built to shuttle supplies to the workers at drop-off points along the cliff edge. Evidence of the trails exists today. Approximately two dozen men worked on the Flume. Workers may have been suspended from ropes to hand drill holes into the sandstone cliff and install iron support rods. In addition to the workers being suspended from above, there is evidence that some of the Flume was constructed using a derrick which traveled in the Flume. The derrick would have extended outward from a completed portion of the flume, similar to the cantilever method of erection used for modern bridges.

Figure 3. Miocene bracket flume (hanging flume), California, c. 1881 (Chico State University archives).

The Hanging Flume is in poor condition and is deteriorating. Where protected from the effects of weather or debris falling from above, large support timbers remain. Segments which were accessible had timbers sawn off and boards scavenged for local construction and mining. Where access was more difficult, even the boards remain. From these protected segments were obtained dimensions, wood species, connection types and construction details.

The Flume, constructed with locally harvested Ponderosa pine (*Pinus ponderosa*), used structural timbers for support, boards to serve as the liner for the Flume, iron rods and metal fasteners. The timbers still in place are deteriorating due to weathering, decay fungi and minor insect attack. As the decay progresses, the timbers eventually fall from the iron rods that hold them to the rock face. Numerous timbers are still in place but severely deteriorated, the result of non-durable wood being exposed to moisture for over a century. Water collects on the upper surface and in the checks and splits in the timber, creating conditions favorable for decay. Decay can also be found at connections where moisture is retained within the timbers. Timbers that are somewhat sheltered from rain and snow have performed admirably considering their exposure and the lack of maintenance since construction of the Flume.

3. DETAILED SURVEY OF THE FLUME CONSTRUCTION

The hanging portions of the Flume are supported on a predominantly vertical cliff face above the Dolores and San Miguel Rivers, so rappelling provides the only means of access to the structure (Figure 4). Structural engineers from Robert Silman Associates, P.C. (RSA) were assisted by the industrial climbing team from Vertical Access, LLC (VA). The survey routine generally consisted of one RSA engineer rappelling down to the structure with one VA technician. The RSA engineer measured and sketched key elements observed at the location (know as a “drop”). The VA technician assisted in taking measurements (Figure 5), took medium format photographs, and operated a video camera with a live feed to a station “topside” (above the top of the cliff face).

The engineer at the structure communicated with the topside engineer and other investigation team members via walkie-talkie, narrating the significant structural systems observed, any unique features encountered, the condition of timber and metal components, and geological conditions. The topside engineer responded with questions and requests for more information. This mode of working allowed for additional field notes to be generated remotely by the topside engineer.

Over six consecutive days in April 2004 the team rappelled down to observe the flume in seven distinct locations. The locations were selected to study the various construction configurations on different bents, particularly the bracket-type bents. Among these bents, the team observed four primary types of support (assigned letters A through D), which are described below. Once the main types were established, the team discovered variations in the configuration of individual components, which were notable enough to warrant the designation of sub-types A1, A2, B1, B2, etc. In reality, each bent is subtly different in its exact dimensions, components, anchorage, and fastener locations, and this typology could be developed further.

Despite the differences between types, construction of the flume box from the bent upward seems to have been relatively uniform along its length. It also strongly resembles some earlier California flumes documented by mining engineer August Bowie, Jr., in his *Practical Treatise on Hydraulic Mining in California* (Bowie, 1885), so the team decided to use Bowie’s terminology in describing the Uravan flume (Figure 6).

The bents typically support two lines of longitudinal stringers, designated inboard and outboard. The stringers, in turn, support transverse sills at roughly 4-foot intervals. In relatively straight sections, half the sills occur more or less directly above a bent, and the other half near mid-span of the stringer. In tight turns, however, the bents typically were installed in the most expeditious location while the sills were offset and rotated to fine-tune the flume box’s shape.

Figure 4. Engineers and industrial climbers rappel to a relatively intact section of the Hanging Flume.

Figure 5. Engineers and industrial climbers measure and document the Hanging Flume at a drop site along the San Miguel River.

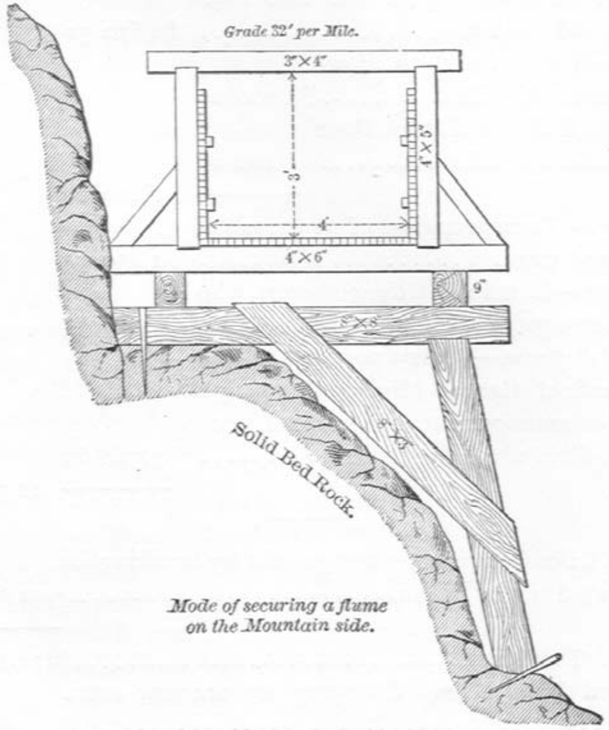

FIG. 18. MILTON FLUME.

Figure 6. Drawing of typical wooden flume, Milton Flume, California (Bowie, 1885).

The flume box proper begins with longitudinal floor planks laid atop the sills. Vertical side posts typically are set in notches in the top face of the sills, with a gap left so that the longitudinal wall planks can be nailed into the side grain of the floor planks. The notch is typically oversized and cannot provide much overturning resistance, so other structural elements are required to keep the flume box walls from spreading outward. Bowie's drawing of the Milton flume shows two possible solutions, horizontal ties above the flume box and diagonal kickers extending from roughly mid-height on the side posts to an outward extension of the sill. It appears that only the first option was used on the Hanging Flume. Horizontal ties are clearly visible in historic photographs (although none were observed within the scope of this survey). Sills on the Flume are not much longer than the flume box is wide, so it would have been impossible to install diagonal kickers.

All five types of flume support (four brackets and one possible trestle bent) observed within the scope of this survey perform the same basic function: providing vertical support to the flume box while also restraining its lateral movement. It is impossible to know whether the flume's original builders used empirical rules to select the sizes of members, or whether they considered certain combinations of vertical and horizontal loading in a mathematical analysis. On the other hand, the configuration of members and detailing of connections do provide some clues as to the builders' thinking. Some parts of the flume reflect an understanding of structural behavior very much in line with current engineering practice, while other areas might be considered "bad detailing" by a modern engineer.

All four types of bracket include direct anchorage to the cliff face at or near the inner end of the horizontal beam, and an indirect support toward the outer end. In types A, B, and C, an inclined timber provides the outboard support, transferring loads along a diagonal path to the cliff face at a point below the beam. Type D differs in that loads are transferred upward, through a combination of metal rods acting in tension and timber braces acting in compression.

Type B brackets, illustrated in Figure 7, are the most simple, consisting of a metal anchor rod at the cliff face, a horizontal beam, and a diagonal brace extending downward. At least three variants of anchor rod configuration were used, one of which used a flat strap washer (Figure 8). Structural analysis of this type is straightforward because the horizontal beam is supported in just two places. If the anchor rod connection and the beam-brace connection are considered to act as "pinned" supports, capable of transferring vertical load but free to rotate, the load going to each can be calculated by hand using arithmetic. In reality, these supports offer some resistance to rotation, but due to the crushing of timber against the fastener, that is not a reliable load transfer mechanism.

In type A brackets, illustrated in Figure 9, the beam is supported in three or more places. Like type B, there is a metal anchor rod at the inner end of the beam, connecting it to the cliff face. At most type A brackets, the cliff face includes an overhang or projection that prevents the flume box from being located immediately next to the anchor. In response to this condition, type A has another metal rod attached to the beam closer to the flume box and anchored into the cliff face some distance above it. This supplemental inclined rod acts as

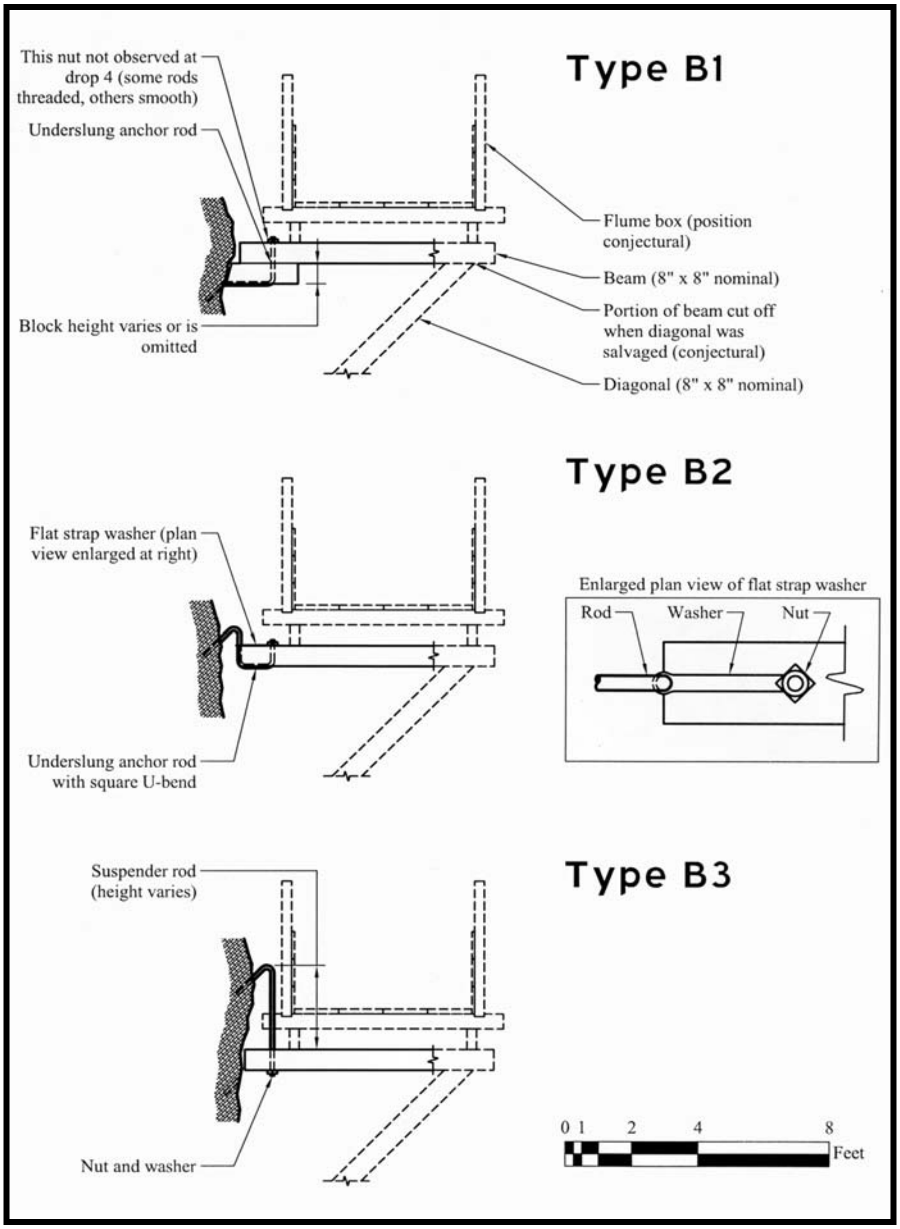

Figure 7. Diagram of type B brackets found along the Hanging Flume.

Figure 8. Anchor rod configuration using a flat strap washer.

an intermediate support, reducing the beam's span and its maximum level of bending stress. While this third point of support makes the division of loading a more complex calculation, it is safe to say that the supplemental rod takes approximately half of the vertical load.

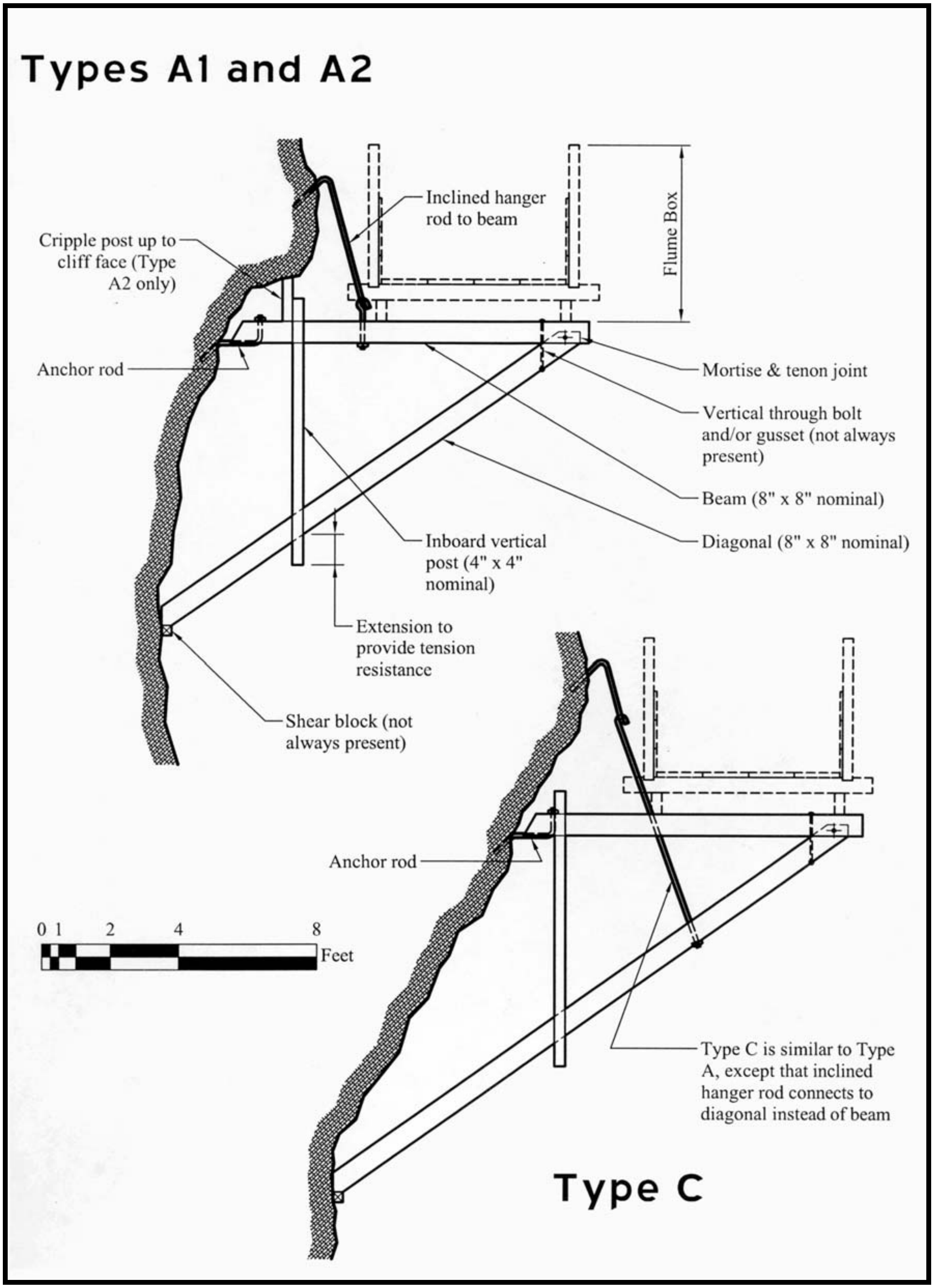

Figure 9. Diagram of type A and C brackets found along the Hanging Flume.

Due to the relative stiffness of the beam, the supplemental rod in type A brackets also becomes a fulcrum: as the beam's outer end deflects downward, its inner end pivots upward, exerting an uplift load on the cliff-face anchor. Type A2 is a more effective variant of this design wherein the inner end of the beam has a timber block wedged against the overhanging rock. The block effectively is a fourth point of support, resisting the uplift load in axial compression. Where an inboard vertical post is included on a type A bracket, this post also experiences tension due to uplift. The fact that the post extends past the connection at either end, providing significant tensile capacity, indicates that the flume's original builders anticipated this function.

Type C brackets, also illustrated in Figure 9, appear very similar to type A, but closer inspection reveals that the supplemental inclined rod is connected to the diagonal brace instead of to the horizontal beam (Figure 10). This arrangement represents a far less efficient a use of material than type A. Because it is not directly loaded by the flume box, the brace benefits far less from an intermediate vertical support. Furthermore, because the inclined rod is effective only in tension, it cannot really prevent the diagonal from buckling. The supplemental rod's only useful function is to reduce the diagonal's sag under its own weight. Structural analysis supports this conclusion.

Figure 10. An example of type C brackets in a segment of the Hanging Flume.

It seems reasonable to conclude that the supplemental inclined rod was intended to reduce bending stresses in the horizontal beam, as it does in types A1 and A2, and that type C represents a misinterpretation of that intent. The question to be answered in a future reconstruction is whether to preserve such anomalous conditions, which might be acceptable when the flume box is missing or empty, but would exceed modern allowable stress levels under full loading.

Where the cliff face included a particularly deep overhang, the flume's original builders responded by developing a type of bracket that, more than any other, justifies the name "hanging flume." Because they are not susceptible to buckling, hangers in tension typically are a more efficient use of material than compression elements. Realizing this, the flume's builders eliminated the downward diagonal brace and substituted a hanger rod inclined upward where they felt confident that the overhanging rock could support the flume's weight. The hanger rod could not simply angle upward from beam to cliff face, however, because this would not leave enough room for the flume to pass through. The solution, called bracket type D and illustrated in Figure 11, is for a vertical rod to ascend from the beam to a point above the flume box, followed by a second segment of rod ascending at a steeper angle to the cliff face (Figure 12). The change in angle represents a change in the direction of force in the hanger, which is resolved through two timber elements, a "bent post" down to the beam, and a "bent brace" in toward the cliff face. Because the bent post and bent beam carry smaller forces than the diagonal brace found on other brackets, type D uses less heavy timber, albeit at the expense of greater complexity.

The final type of support observed is a trestle bent, called type T, also illustrated in Figure 11. Trestle bents are structurally straightforward, consisting of a beam and two posts (either vertical or, as in Bowie's drawing of the Milton flume, leaning inward at a slight angle). Timber gussets at each intersection of post and beam provide lateral stability.

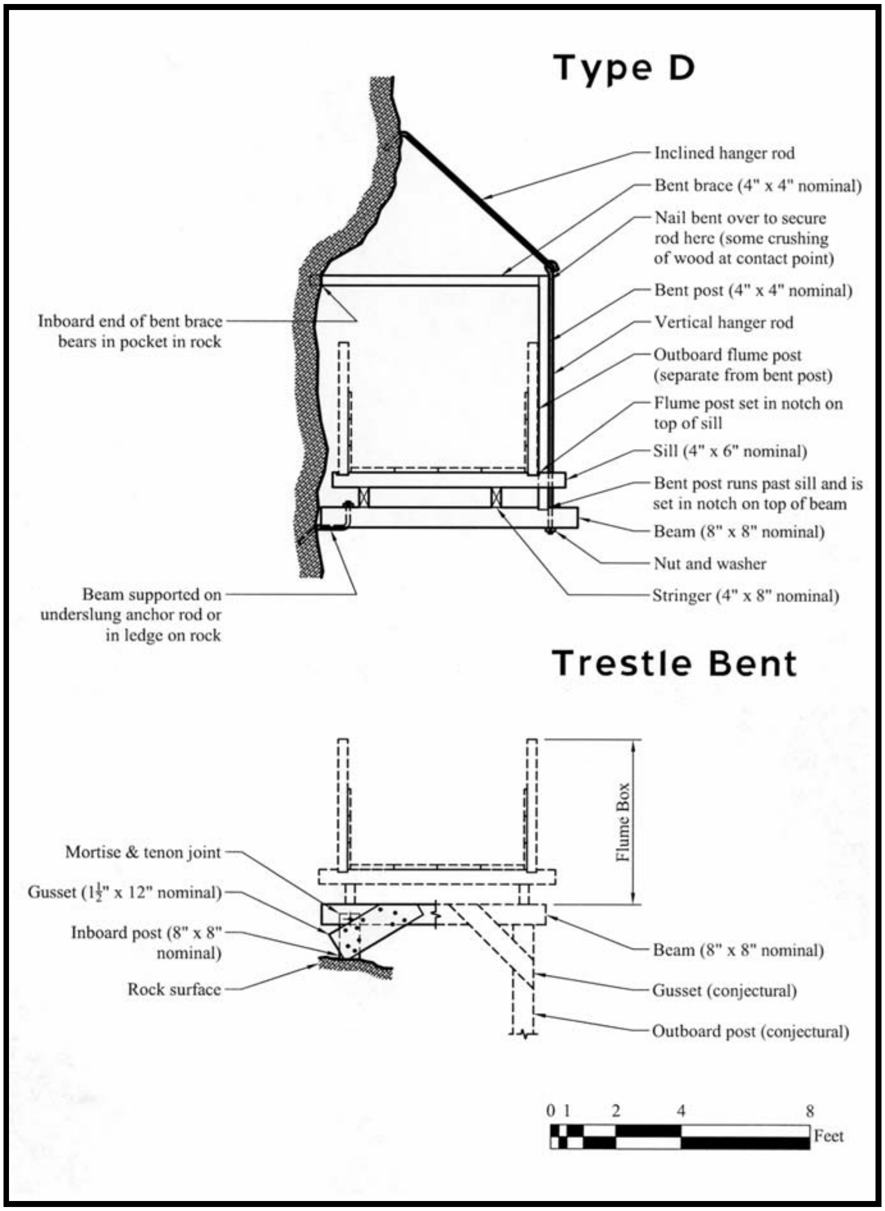

Figure 11. Diagram of Type D brackets and trestle bents found along the Hanging Flume.

Figure 12. An example of type D brackets found in one segment of the Hanging Flume.

4. RECONSTRUCTION CONSIDERATIONS

Based on preliminary structural analyses of a limited number of bents measured in the field, we concluded that they are more than adequate to carry loads imposed by an empty flume box. The resulting factor of safety implies that some members can safely carry load even if their cross-sectional area is reduced slightly by deterioration. While this speaks to the possibility of leaving existing historic fabric in place as part of a reconstructed flume segment, more detailed analyses would need to be performed to establish a maximum tolerable level of deterioration before a given member must be replaced. Also, the issue of long-term durability must be addressed by considering options such as applying preservatives or modifying historic details in areas that are particularly vulnerable to deterioration.

The existing bracket configuration, timber condition, rock quality, and cliff geometry all change from bent to bent. A great deal of effort would be required for a structural engineer to perform field measurements and detail connections for each individual bracket in reconstruction contract documents. An alternative strategy would be to establish typical details for certain situations such as repair of lightly and heavily deteriorated brackets; reconstruction of missing brackets on vertical, sloping, or overhanging cliff faces; etc. These might resemble the four bracket types that were documented by this survey. Other typical details would cover flume box reconstruction on straight sections, on outside bends, and on inside bends. In this approach, the reconstruction essentially would be designed by the tradesmen performing the work on site, although their decisions would be constrained by certain rules set by the structural engineer.

Although the structural engineer will be directly responsible for structural analysis and design, the entire preservation team should be included on the development of design criteria. Replacement bracket configurations should be based on a thorough understanding of how the original builders responded to changing conditions on site. Replacement connection details should fit into the context of how the builders altered their use of various fasteners over time. There undoubtedly are many more non-structural criteria that are not familiar to modern structural engineers and contractors. These should be communicated in the form of a specification or standard developed by the governing historic preservation agency.

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