

Exponent[®]


Engineering Management Consulting

**Moss Landing Tower Collapse
Root Cause Analysis**



Moss Landing Tower Collapse Root Cause Analysis

Prepared for


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April 4, 2016

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Limitations

At the request of Pacific Gas & Electric Company (PG&E), Exponent conducted a root cause assessment of electric transmission tower collapse on October 18, 2015 resulting in significant equipment and structure damage as well as customer outages. Exponent has investigated specific issues relevant to the incident as requested by PG&E. The scope of services performed during this investigation, as well as our findings as described herein, may not adequately address the needs of other users and any re-use of this report, conclusions, or recommendations presented herein are at the sole risk of the user.

The findings presented herein are made to a reasonable degree of engineering and scientific certainty based on observations and information available at the time of the investigation. This report may be supplemented to expand or modify our findings based on additional work or review of additional information. Thus, if new data become available or there are perceived omissions or misstatements in this report, we ask that they be brought to our attention as soon as possible so that we have the opportunity to fully address them.

Executive Summary

On October 18, 2015, a PG&E electric transmission tower located in Moss Landing, CA collapsed. The tower was a 124-foot tall, steel lattice, overhead transmission tower of a type designated by PG&E as G95-DE with a 32.5-ft extension. The tower supported two circuits (Metcalf – Moss Landing 1 and Metcalf – Moss Landing 2), each composed of three 954 KCMIL Cardinal ACSS conductors (1.196” diameter) spanning 252 feet to the east, and three bundled (paired) 1113 KCMIL Marigold AAC conductors (1.216” diameter) dropping to the substation to the south^{1,2}. The tower was of bolted steel construction whose basic design is shown on PG&E Drawings 403912 (Rev. 8) and Rec. 622028.

PG&E retained Exponent Failure Analysis Associates (Exponent) to investigate the direct and root cause(s) of the accident, and in particular, to evaluate the tower design and material properties for possible contribution to the collapse. Exponent prepared two reports for this investigation: a structural and metallurgical failure analysis report² and this report to identify the root cause. Based on the failure analysis, Exponent² identified two principal findings relative to the tower collapse:

- Based on measurements made of the foundations after the accident, the stub angles were not oriented correctly at the time of construction. Rather than being tilted to match the sloped tower legs, the stub angles were installed with insufficient batter (angle); therefore, causing a misalignment of the stub angles and lower tower legs. When the bolts were tightened to bring these components together, the out-of-alignment configuration produced bending moments in the stub angles which exceeded the stress limits in the stub angle material.
- Based on metallurgical examination and testing of steel specimens of the stub angles recovered from the site, the steel met the mechanical and chemical requirements for ASTM A572 Grade 50 at the time of the specification and purchase. The accident fracture surfaces and subsequent testing indicates that this steel is more brittle than desirable for the subject tower application. However, the tower would not have collapsed if the stub angles and lower legs were aligned as-designed. PG&E is in the process of updating its material specifications to include fracture toughness requirements.

¹ Drawing No. 076274, Rev. 6, Page 10

² Reference 1: Exponent Failure Analysis Report

Based on the results of the failure analysis and a review of the available documentation, Exponent defined the problem statement for the root cause analysis as:

“On October 18, 2015, a 124-foot electric transmission steel lattice tower collapsed in Moss Landing, California, due to the incorrect installation of the footing stub angles during foundation construction, resulting in the collapse of the tower and damage to adjacent structures.”

From the findings identified, the tower collapse event was initiated by the incorrect settings of the stub angle due to a human error in reading the drawing heel batter; and the subsequent communication of this incorrect heel batter to the crew for use in setting the stub angles³. Human errors may occur for a variety of reasons, but work processes and programs are put in place to prevent human errors from having significant consequences. Typical human error defenses (barriers to prevent human error) include training, procedures, clear documents and communication, and independent verification. Since the human error relative to the stub angle alignment with the tower legs resulted in a significant occurrence, the causal analysis includes a review of these barriers and their performance and contribution to the incident.

Based on the causal evaluation, the root and contributing causes of the incident are listed below. The root cause is based on determining whether eliminating the cause would have prevented or significantly reduced the probability of the incident, and whether eliminating the cause is under the control of management. Contributing causes are those that may contribute to preventing the event.

- ***Root Cause: Inadequate process to ensure that critical parameters (dimensions and/or steps) of the transmission towers are constructed as designed:*** The verification methodology to ensure that design information from the tower drawings is correctly transferred to the construction installation process should be improved. There is no formal requirement to verify the take-offs from the drawings. Since the stub angle inclination is a key dimension for validating the tower design, a defined means to determine and confirm this dimension (as well as other key parameters) is required.
- ***Contributing Cause 1: Inadequate process design relative to training requirements for tower drawings for transfer of design-related information to the construction crews:*** The tower construction utilizes general drawings and not site specific drawings. There is no formal training that provides the construction crew with information on what drawings to review and how to interpret these drawings. Also, the key parameters that govern the design are not communicated except through informal on-the-job (OJT) training. Formal training provides a basis for understanding requirements and gaining necessary information on significant design considerations as impacted by construction

³ Since the identification of the human error occurred approximately nine months after the stub angle setting, it is expected that the recollection of specific events from interviews may be imprecise.

activities. Also, tower erection is not performed frequently and the use of OJT exclusively may no longer be sufficient.

- ***Contributing Cause 2: Inadequate maintenance (update) of drawings relative to legacy tower drawings may not reflect the current needs of crews who perform the tower installations on an infrequent basis:*** The tower drawings are very dated and last updated in the 1960's. Therefore, this causes the potential for error in reading the drawings due to legibility issues, as well as missing or confusing information.
- ***Contributing Cause 3: Inadequate process design relative to training requirements for tower drawings on dimensional tolerances and potential field issues:*** This cause is similar to Contributing Cause 1, except that it relates to the field identification of potential issues. There is no formal guidance provided to the crews relative to fit-up tolerances on critical dimensional measurements, and other field observations that may indicate a problem.

Recommended corrective actions are identified and included in Section 7. This Executive Summary does not contain all of Exponent's technical evaluations, analyses, conclusions and recommendations. Hence, the main body of this report is, at all times, the controlling document.

1. Background

1.1 Tower Design and Event Description

On October 18, 2015, a PG&E electric transmission tower located in Moss Landing, CA collapsed. The tower was a 124-foot tall, steel lattice, overhead transmission tower of a type designated by PG&E as G95-DE with a 32.5-ft extension. The tower supported two circuits (Metcalf – Moss Landing 1 and Metcalf – Moss Landing 2), each composed of three 954 KCMIL Cardinal ACSS conductors (1.196” diameter) spanning 252 feet to the east, and three bundled (paired) 1113 KCMIL Marigold AAC conductors (1.216” diameter) dropping to the substation to the south^{4,5}. The tower was of bolted steel construction whose basic design is shown on PG&E Drawings 403912 (Rev. 8) and Rec. 622028.

The tower was constructed in the following sequence:

- March 18-19, 2015: The four concrete foundation piers (with embedded and protruding stub angles) were set on March 18 and poured on March 19.
- April 6-8, 2015: Construction of the base (lower tower extensions) occurred at this time. The tower was constructed piecewise by first erecting a 17.5-ft extension (lower tower legs, diagonal lacing, and horizontals), and then a 15-ft extension to complete the base.
- September 8, 2015: After the base was erected, the remaining tower structure, which had been pre-assembled on site, was placed atop the base with a crane after clearances were received.
- September 12, 2015: The wire transfer operations were conducted for Metcalf-Moss Landing Circuit 1.
- October 10, 2015: The wire transfer operations were conducted for Metcalf-Moss Landing Circuit 2.⁶

⁴ Drawing No. 076274, Rev. 6, Sheet 10

⁵ Reference 1: Exponent Failure Analysis Report

⁶ Detailed tower information from Reference 1

The tower collapse occurred on October 15, 2015 and Figure 1 shows a photograph of the site shortly after the tower collapse.⁷



Figure 1: Moss Landing Tower Collapse Site Photo

1.2 Failure Analysis Findings

PG&E retained Exponent Failure Analysis Associates (Exponent) to investigate the direct cause(s) of the accident, and in particular, to evaluate the tower design and material properties for possible contribution. The Exponent failure analysis results are included in Reference 1 and a summary is provided below.

Exponent's failure analysis investigation included:

- Site visual inspection
- Measurements and photo-documentation of the accident site on the day of the accident
- Collection and storage of key physical evidence
- Structural analysis of the subject tower under expected loads during construction, and at the time of the accident

⁷ Reference 1: Exponent Failure Analysis Report

- Review of design documents and summaries of the design and construction process for this tower
- Verification of selected tower design loads and member sizes as they relate to the accident
- Metallurgical analysis
- Mechanical properties testing of steel specimens recovered from the accident site, as well as exemplar material provided by PG&E
- Finite element-based stress analysis
- Linear-elastic fracture mechanics analysis

The subject tower supported two circuits designated as Metcalf – Moss Landing 1 and Metcalf – Moss Landing 2. Both circuits made an approximately 90 degree angle at the tower, resulting in a net overturning load to the southeast⁸. Figure 2 shows the foundation layout of the tower and the location of the conductors for illustrative purposes. The tower toppled to the southeast after failure of the stub angles. The stub angles at legs B and D exhibited corroded fracture surfaces at the time of collapse, indicating that these developed cracks prior to the tower collapse⁹. The stub angles at legs A and C showed no signs of corrosion, indicating that they most likely failed at the time of the collapse.

⁸ Structural Data Sheet 233101, Rev. 8

⁹ There is no method of determining when these stub angles cracked although the cracks could have occurred between the time of erection of the base (lower tower extensions) and weeks to months prior to failure to allow for corrosion to develop.

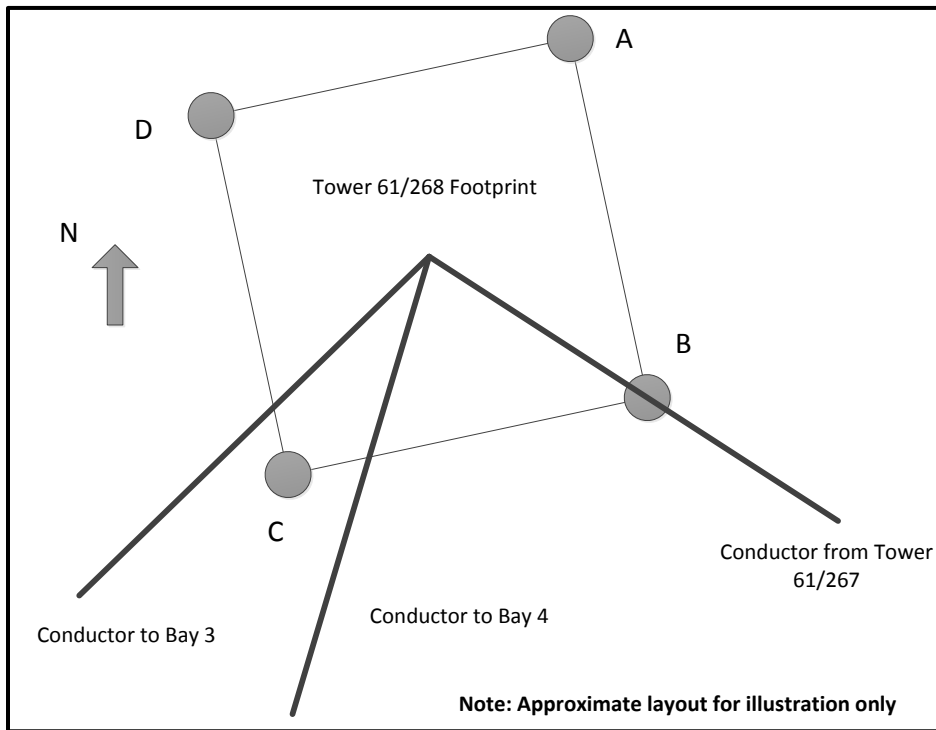


Figure 2: Tower Foundation Layout and Conductor Location

Based on the failure analysis, Exponent¹⁰ identified two principal findings relative to the tower collapse:

- Based on measurements made of the foundations after the accident, the stub angles were not oriented correctly at the time of construction. Rather than being tilted to match the sloped tower legs, the stub angles were installed with insufficient batter (angle). The correct heel batter angle is $2\text{-}5/8^{\circ}$ ¹¹. The as-built (as-measured) heel batter of the foundation stub angles was too steep relative to the design drawings, and as such, the top of any tower leg bolted to them would have been significantly outboard of its intended position.¹² Figure 3 provides an illustration of this condition.

The “as-designed” requirements for the stub angles is that the lower legs and stub angles are parallel (as shown in the left graphic in Figure 3) such that there is no lateral force (F) or bending moment (M) on the stub angle. The “as-built” configuration measured in the field after the tower failure showed that the stub angle and lower leg were out-of-alignment (as shown in the right graphic in Figure 3). When the bolts were tightened to

¹⁰ Reference 1: Exponent Failure Analysis Report

¹¹ Drawing 313438 and Rec 621915

¹² Reference 1: Exponent Failure Analysis Report. The as-measured heel batter was $1\text{-}5/8^{\circ}$ for three of the stub angles. The fourth stub angle was measured at $1\text{-}3/4^{\circ}$.

bring these components together, this produced bending moments in the stub angles which exceeded the stress limits in the stub angle material and resulted in the failure as identified in Reference 1.

- Based on metallurgical examination and testing of steel specimens of the stub angles recovered from the site, the steel met the mechanical and chemical requirements for ASTM A572 Grade 50 at the time of the specification and purchase. The accident fracture surfaces and subsequent testing indicates that this steel is more brittle than desirable for the subject tower application. This brittleness made the stub angles more sensitive to normal, and expected damage around the punched bolt holes, and thus more vulnerable to brittle fracture under the stresses induced during construction fit-up misalignment. It is noted that the chemical requirements for A572 Grade 50 steel have been tightened since the time of specification and purchase of the subject stub angles, and that the purchased steel would not meet the new requirements. However, the tower would not have collapsed if the stub angles and lower legs were aligned as-designed. PG&E is in process of updating its material specifications to include fracture toughness requirements. PG&E is currently in the process of updating its material specifications relative to requirements for fracture toughness, and to hole punching and reaming requirements in Specification 30. These updates address Exponent recommendations 2 and 3 in Reference 1¹³ and additional safety margin against fit-up issues. PG&E has also addressed Exponent recommendation 4 to determine if a similar condition exists at other towers. This assessment is discussed under “extent of condition” in Section 8.

Based on the results of the failure analysis, the problem statement is prepared as discussed in Section 2.

¹³ Reference 1: Exponent Failure Analysis Report, Executive Summary

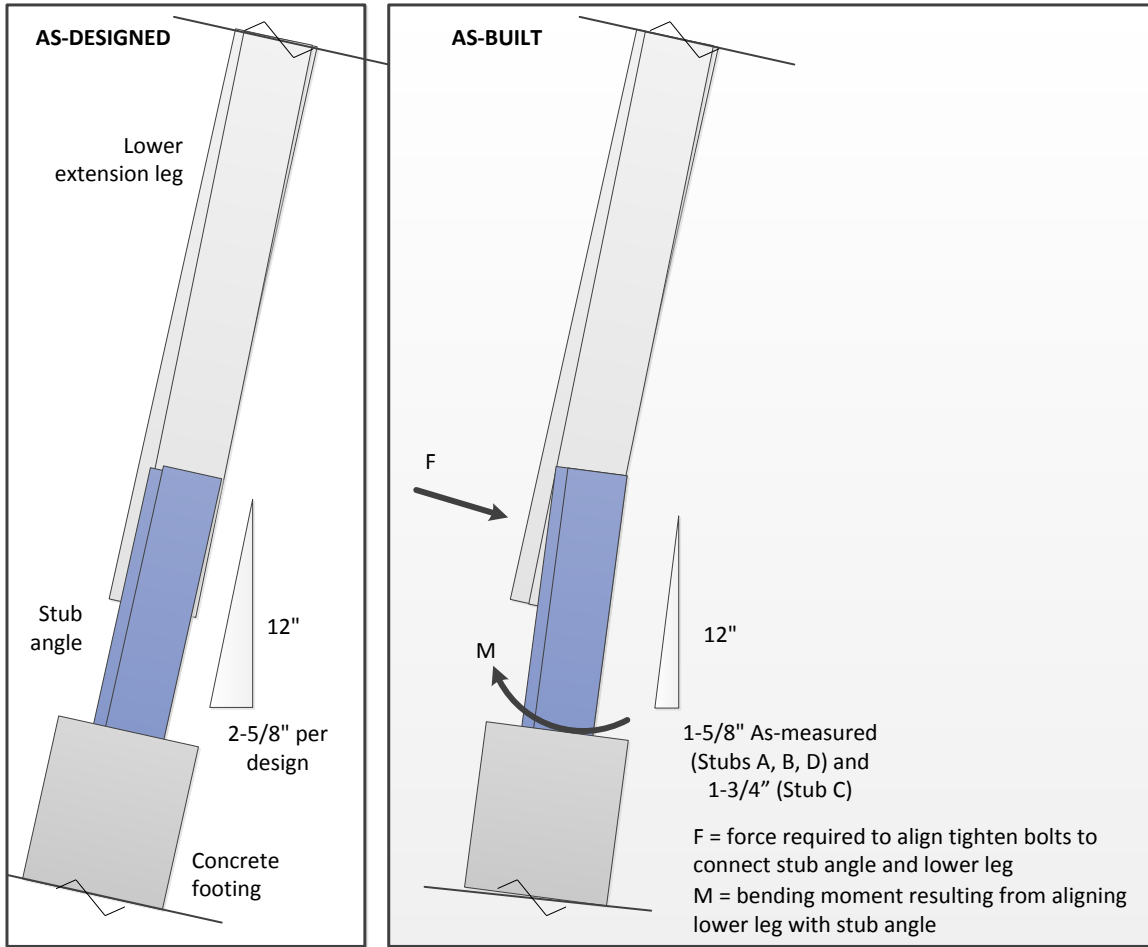


Figure 3: Stub Angle – Lower Tower Leg Orientation (for illustrative purposes only)

2. Problem Statement

The problem statement provides the focus of the root cause analysis to ensure that the appropriate issues are addressed. Based on the results of the failure analysis (reference 1), and a review of the available documentation, Exponent defined the problem statement for the root cause analysis as:

“On October 18, 2015, a 124-foot electric transmission steel lattice tower collapsed in Moss Landing, California, due to the incorrect installation of the footing stub angles during foundation construction, resulting in the collapse of the tower and damage to adjacent structures.”

3. Root Cause Analysis Approach

The approach used in both this investigation and the causal analysis are summarized here to provide context for the discussion and results presented in this report. From an overall causal analysis perspective, there are three main types of barriers to the prevention of an unwanted event; (1) Physical Controls, (2) Processes and Procedures, and (3) Management Policies and Organization. These barriers are generally depicted in Figure 4.

Causes of major incidents or losses typically involve management policies and organizational interfaces that inadvertently degrade the effectiveness of the various barriers in place¹⁴. For this reason, all types of barriers are reviewed and corrective measures identified to strengthen each individual type of barrier.

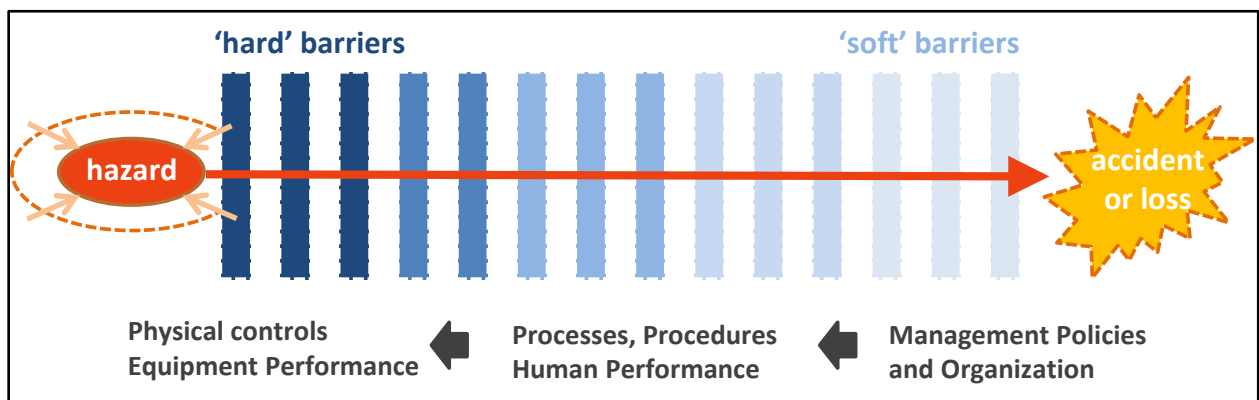


Figure 4: Prevention of Unwanted Events

The root cause assessment team evaluated this incident in accordance with a structured approach for causal and failure analysis consisting of the following five (5) steps:

- **Data Collection**

Data collection¹⁵ was performed through a review of event-related documents and follow-up interviews, as well as discussions with other subject matter experts.

¹⁴ Conditions are hidden deficiencies in management control processes or values that create workplace conditions capable of provoking errors and degrading the integrity of defenses (Reference 12: US Department of Energy, Human Performance Handbook, Human Performance Improvement Concepts and Principles, 2007).

¹⁵ Initial event data collection, including interviews, drawing, manuals and analysis was prepared by PG&E and was utilized in the root cause analysis.

- ***Reconstruction of Problem Scenarios***

As a result of the data collection activities and the direct cause analysis (Reference 1), a sequence of events was developed around specific activities for use in evaluating the incident.

- ***Performance of Causal Analysis***

The causal analysis was performed in a structured sequence of steps that led to identification of the root and contributing causes. The cause analysis tools used in this investigation were:

- a. Events and Causal Factors Analysis (ECFA) – This tool is used to identify potential systemic incident causes (i.e., management policies and organization) for each initiating event. It involves repeatedly asking *why* the event or pre-condition existed in order to identify the underlying causes. This tool was used for the primary causal analysis.
- b. Causal Factor Unit Analysis – This step involved a detailed evaluation of each cause identified in the ECFA, and was used to determine the root cause(s) of the incident. It involves assessing the degree to which each condition contributing to the incident is within management’s control to change, and whether its removal would have prevented the occurrence of the problem. Those causes which meet these criteria were determined to be the root cause(s) of the incident.

The outcome of the above causal analyses was the identification of the root and contributing causes. This information formed the basis for assessing lessons learned and corrective actions.

- ***Review for Extent of Condition***

An outcome of the causal analysis is to identify the potential for the problem or cause to exist elsewhere.

- ***Development of Recommended Corrective Actions***

The desired outcome of the causal analysis is to identify recommended corrective actions to prevent recurrence of the problem, and to identify lessons learned. Effective corrective actions are those that address the causes, are implementable by the organization, are cost effective and are consistent with company business goals and strategies.

4. Data Collection and Analysis

The data collection and analysis was performed primarily through review of records provided by PG&E, as well as supplemental interviews with project participants and subject matter experts. The kick-off meeting for the root cause investigation was held on January 27, 2016. Since the incident's occurrence in October 2015, PG&E has performed interviews, data collection and analysis. Exponent has built on that information for use in this analysis. The principal sources of information used in this analysis are:

- Documentation (see Section 10 References for a list of documents reviewed)
- Interviews (see Appendix A for list of interviewees)¹⁶

The timeline for the incident was developed from the time of “submittal of the job package to construction” through the “incident”. This time frame provides for a complete review of actions, processes, and requirements leading up to the tower installation job and the events of October 18, 2015. The data collection and analysis is performed to develop an event timeline (or sequence of events) and to compare the job's as-required processes to the as-performed processes in order to identify gaps and actions that may not be in accordance with PG&E expectations. These gaps and actions are the starting point of the causal analysis.

The key activities reviewed in the data collection are:

- Job package completeness
- Construction foundation planning
- Foundation set-up and prep
- Setting and installation of the stub angles
- Verification of stub angle placement
- Installation of lower tower extensions

The results of the data collection are provided in the following:

- Sequence of events (see Appendix B)
- Findings descriptions and evidence chart (see Appendix C)

¹⁶ Since the identification of the human error occurred approximately nine months after the stub angle setting, it is expected that the recollection of specific events from interviews may be imprecise.

The timeline in Appendix B provides a detailed description of the timeline and process comparison; and identifies the gaps and actions that may not have been performed according to PG&E expectations. These findings are described in Section 5 and Appendix C.

5. Observations and Findings

Background information is presented in this section to describe the sequence of events and the findings and observations from the data analysis that are the basis for initiating the causal analysis.

5.1 Sequence of Events

The reconstruction of the problem scenario is described in the sequence of events as shown in the chart in Appendix B. The sequence of events is described for the tower design and installation. The key activities defined for the tower design and installation are:

- Engineering and design is performed and a job package is created and provided to construction¹⁷. The tower design is based on existing drawings for the G95 tower type.
- The selection of the crew for the tower installation is made by the construction supervisor¹⁸. The crew foreman and crew lead have prior experience with tower construction. However, this is the first G95 tower installation that the crew foreman has led.¹⁹ While experience with G95 towers was limited, the crew had tower experience, and the construction process for the tower and foundation was performed as intended.
- The tower installation project is reviewed by the supervisor and crew foreman and scheduled through the project manager.¹⁹
- The crew foreman reviewed the job package (structural data sheets and selected drawings) and assigned tasks to the crew (including communicating the stub angle heel batter). The crew foreman's recollection was that he incorrectly communicated the face batter (1-7/8" per 12") as the heel batter (correct 2-5/8" per 12") to the crew based on an incorrect reading of the drawing (Rec. 621915).¹⁹ However, the actual heel batter from the field measurements was 1-5/8" for 3 stubs and 1-3/4" for the fourth batter (see Figure 3). There is no procedure or requirement that specifies the independent check of the stub setting dimensions obtained from the drawing, prior to the initiation of field construction activities.²⁰

¹⁷ Reference 2: Job Package

¹⁸ Interviews with construction staff and supervisor

¹⁹ Interviews with crew foreman

²⁰ Mitigation of operator mistakes (cognitive perception or interpretation malfunction) often require external monitoring/checking from qualified, experienced, and independent personnel due to the perpetrator having limited clues there is a problem (Reference 13: Bea, R.G. Human & Organizational Factors: Quality & Reliability of Engineered Systems, Volume 1. 2008).

- The crew performed the tasks of locating the tower footing locations; placing the stub angles; and completing the concrete pour to establish the tower footings. The crew followed appropriate procedures as identified in the Template Setting Manual. [Note that the site surveys after the event and during the failure analysis indicated that the stub angles were positioned to the incorrect heel batter angle, communicated by the foreman.²¹]
- The crew performed a series of verification activities at the location, during setting and concrete pour activities for the stub angles and footings. These activities are identified in the Template Setting Manual and include the following:
 - Verification of stub angle batter and alignment within the footprint of the footings through use of measurement tools (transit, plumb bobs, angle measuring tools, tape measures), that monitor stub angle setting during setting of individual stub angles, after completing all stub angle settings, and during the concrete pour. The dimensions taken off the drawing by the foreman and verbally communicated to the crew, is the basis for each verification step performed.
 - Additional measurements are taken between the stub angles and diagonally across the foundation footprint.
 - Height measurements are also taken at the tops of the stub angles to ensure that the foundation is appropriate to accept the lower tower extensions.

Through the interviews with the crew foreman and crew lead, the measurements were all at the approximate requirements of the drawings. Length measurements between footings were reported as within 5/8”²². There is no guidance provided for tolerances on the footing measurements.

- The crew erected the tower base (17-1/2 foot base extension), and indicated that there was no significant issue with completion of this activity, and that it was similar to other tower projects. There was no identification of the misalignment of the stub angles.²³
- The crew completed the remaining upper tower erection.
- The linemen installed the conductors.
- The construction crew completed the as-built package and submitted the project for processing. There is no indication on the as-built drawings that there were any issues with the stub angles or tower erection.²⁴

²¹ Reference 1: Exponent failure analysis report

²² Interview with crew foreman and crew lead

²³ Interview with crew foreman and crew lead

²⁴ Reference 3: As-built package

The problem scenario in Appendix B captures the sequence of events and also identifies the observations and findings from the data analysis. These findings and observations are discussed below.

5.2 Observations and Findings

The key observations and findings are identified in the sequence of events in Appendix B and are further described in Appendix C. For purposes of this discussion, observations are actions and conditions that met expected requirements and results. Findings are actions or conditions that did not meet requirements and these findings are used in the causal analysis. A summary of the observations and findings are described below.

Note 1: (Observation) Job package references appropriate drawing

The job package submitted to construction referenced the appropriate design drawings for the foundations and stub angles for the G95 tower.²⁵ Note that not all drawings were included in the actual job package, but drawings were referenced, known by, and available to the construction staff.²⁶ The structural data sheet and drawings applicable to the tower design were structural data sheet 233101; structural drawing 403912; foundation drawing 309933; drawing 313438; and record 621915. These are the appropriate drawings for the construction of the G95 tower.²⁷

Note 2: (Observation) Drawing Age

The drawings for the G95 tower are unchanged over the past 50 years, but the drawings contain correct and appropriate information for erection of the G95 tower. There are issues with legibility of the drawings in the field, but the construction crew has access to personnel at Davis Service Center to assist in reading drawings, if legibility of the copies is an issue.²⁸

Note 3: (Finding) Drawing 313438 not used to determine stub angle heel batter

The structural data sheet references structural drawing 403912 for the G95 tower. This drawing and the structural data sheet references drawing 309933 for the foundations. This drawing references drawing 313438 and Rec. 621915 for additional foundation and stub angle details. The correct heel batter is indicated in Section C-C of drawing 313438. The heel batter is indicated as 2-5/8" per 12". The crew foreman indicated that he did not use this drawing for determination of the heel batter, but used the referenced Rec. 621915 for the heel batter determination. Figure 5 below shows the heel batter designation from drawing 313438.

²⁵ Reference 2: Job package

²⁶ Interviews with crew foreman

²⁷ Interviews with engineering personnel

²⁸ Interviews with crew and engineering; Reference 6: PG&E tower drawings

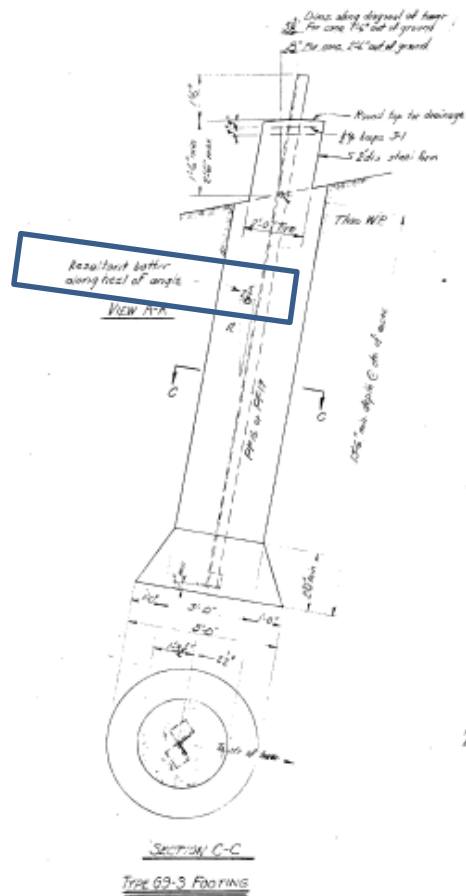


Figure 5: Heel Batter Designation from Drawing 313438

Note 4: (Finding) Misread required batter from Rec. 621915 and miscommunicated to crew

Rec. 621915 is provided for additional foundation and stub angle details. The correct heel batter is indicated in Section C-C of drawing 313438 and also in the diagram in the top right of Rec. 621915. The heel batter is indicated as 2-5/8” per 12”. There is additional information in the diagram in the top right of Rec. 621915 that shows both a face batter and a heel batter, but with no specific identifier (“heel” or “face”) next to the values. Discussions with the crew indicated that the foreman miscommunicated the heel batter to the crew for use in setting the footings and stub angle.^{29,30} The information from Rec. 621915 is shown in Figure 6 below. This incorrect heel batter angle led to a condition which introduced excessive stress on the stub angle (see Note 8 later).

²⁹ PG&E conducted interviews with crew

³⁰ The actual dimension of the heel batter communicated to the crew was based on crew recollection.

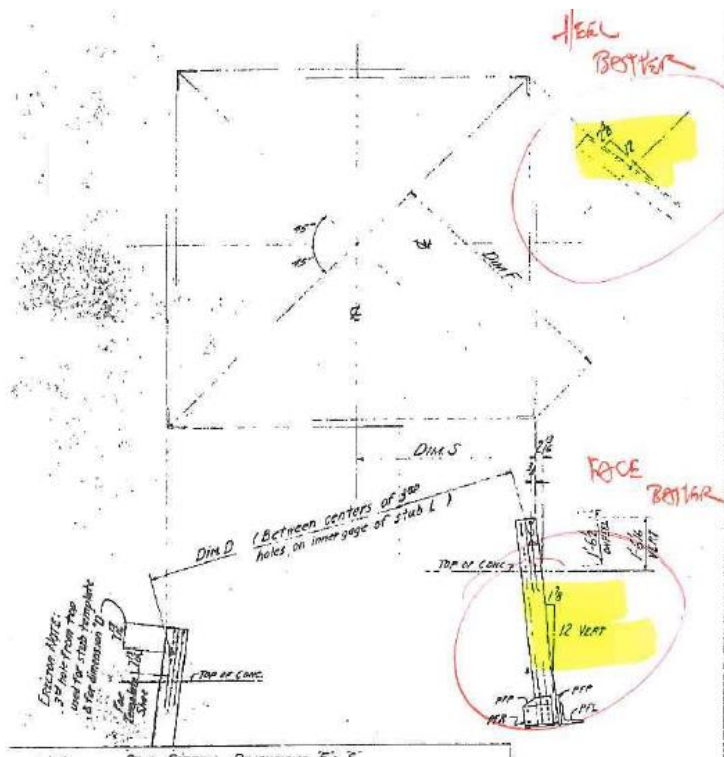


Figure 6: Stub Batter Angles from Rec. 621915

Note 5: (Finding) No formal training on the design basis for the tower design and installation relative to translation of drawing requirements to construction

There are no formal procedures or training for review and interpretation of the information from the tower drawings to the field construction effort. There is reliance for on-the-job training (OJT). Additionally, there was no formal meeting between construction and engineering relative to the requirements for this tower job.

Note 6: (Finding) No formal training on tower foundation setting and erection; template setting manual provides guidance but is not a controlled document

There is no formal training for tower foundation setting and erection. There is reliance for on-the-job training (OJT) and guidance from a template setting manual. However, the template setting manual is not a controlled document and has limited distribution to the crews (mostly resides with supervisors and foreman). The template setting manual has detailed instructions for the actual construction activities associated with the footing and stub angle placement. Based on field inspection after the event, the construction of the footings and stub angles was performed consistent with expectations.³¹ A field demonstration was held on February 24, 2016, at the PG&E Livermore Training Facility. The field demonstration was performed to show how the

³¹ Reference 1: Exponent failure analysis report

footings were located and bored and how the stub angles were set. This demonstration was performed consistent with the template setting manual.

Note 7: (Finding) Stub angle placed at incorrect angle

Three stub angles (A, B, D) were inclined at a batter of 1-5/8" per 12" and the fourth (C) at 1-3/4" per 12" vs. the required 2-5/8" per 12" per the field inspection after the event.³²

Note 8: (Finding) Inspection and verification requirements not adequate (pre-concrete pour and post-concrete pour)

There are no requirements established for independent verification activities for determination of dimensions from the tower drawings.³³ There was no verification of the stub angle batter for this tower erection against the information in the drawing at this location.³⁴

Note 9: (Finding) No guidance on fit-up tolerances

Tolerances are not provided on the tower foundation and stub angle drawings related to the stub angle batter and dimensions between stub angles. Interviews with engineering confirmed that the stub angles are required to match the drawing dimension to validate the design assumptions for the tower. Additionally, there is no guidance provided for dimensional tolerances (e.g. dimensions F and S "to theoretical heel of top of stub", see drawing 313438).³⁵

Note 10: (Finding) No identification of misalignment of stub angles (during fit-up at top of 17-1/2 ft. legs, during installation of bracing, and during bolt tightening)

There was no identification of the stub angle misalignment with the lower tower legs during the tower installation.³⁶ The construction sequence for a tower erection includes significant amount of movement of various members, until the tower bolts are tightened. Therefore, there is limited opportunity for visual clues that there may be a tower erection problem relative to fit-up. The crew indicated that they did not observe anything during this installation that was out-of-the ordinary for tower erection. Additionally, there is no formal training to alert construction crew members on what to look for during construction that may be indicative of a problem.

Note 11: (Finding) Tower collapse

The tower collapsed on October 18, 2015, and caused damage to an adjacent tower. This is the failure event.

³² Reference 1: Exponent failure analysis report

³³ Review of template setting manual and lack of formal procedures

³⁴ Interviews with crew foreman and crew lead

³⁵ Interview with construction crew and engineering personnel

³⁶ Interviews with crew foreman and crew lead

The findings identified above are used as starting points in the causal analysis that follows. Observations were provided to describe a complete picture of the activities and conditions during the tower installation.

6. Causal Analysis

6.1 Causal Analysis

The Event and Causal Factor Analysis (ECFA) is used to evaluate the cause for each of the findings previously determined. The analysis is performed by looking at the causal chain for each finding, based on the evidence and facts gathered during the data collection activities. The ECFA is presented in the causal diagram shown in Appendix D. This section describes the results of the ECFA.

From the findings identified and described in Section 5, the tower collapse event was initiated by the incorrect settings of the stub angle due to a human error in reading the drawing heel batter; and the subsequent communication of this incorrect heel batter to the crew, for use in setting the stub angles. Based on Figure 7, this human error represents an unintentional action (error or slip). Human errors may occur for a variety of reasons, but work processes and programs are put in place to prevent human errors from having significant consequences. Typical human error barriers include; training, procedures, clear documents and communication, and independent verification. Since the human error relative to the stub angle alignment with the tower legs resulted in a significant occurrence, the causal analysis will include a review of these barriers and their failure to prevent the event.

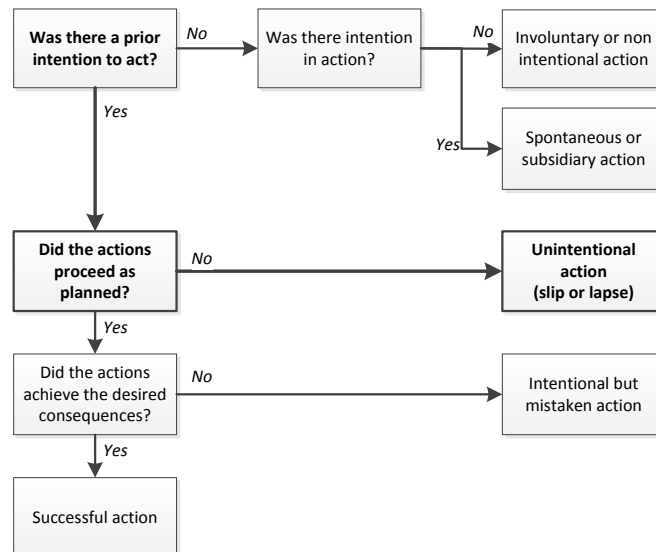


Figure 7: Human Error Classification³⁷

³⁷ Method for determining the type of human error (Reason, J. *Human Error*. 1990)

Based on the causal analysis of the problem statement and the findings previously identified, the causal analysis is provided in the chart in Appendix D, and described below.

The causal analysis chain starts with the tower collapse, which was caused by the stub angles being installed at the incorrect angle (batter).

There are two causes of the stub angles at the incorrect angle:

1. The angle was misread from the design drawings, and this incorrect angle was communicated to the crew for their foundation setting work. Interviews with the PG&E crew foreman indicated that he misread the drawing angle and communicated this incorrect information to the crew.³⁸ Exponent concludes this was a human error. Human errors are typically prevented by processes related to training, procedures and verification.

The first causal chain for this error relates to an insufficient review of the job package. Prior to construction, the crew foreman received all pertinent engineering drawings for setting the foundation of the tower in question.

- During the review of the job package, the foreman indicated that he misread the heel batter inclination on Rec 621915. Additionally, drawing 313438 was not used to determine the heel batter. These actions for ineffective review were caused by inadequate training, relative to transferring design information into the construction plan for the footing set-up. The inadequate training is caused because there is no formal training program for the construction crews on interpreting the design-related information to construction. Currently, on-the-job training is relied upon for transferring knowledge to the crew. This approach may have been effective in the past, but there are fewer towers being constructed today, and the on-the-job training approach may no longer be sufficient. The lack of a formal training program is caused by inadequate program design to identify the need for formal training of the crew, relative to understanding and interpreting the design drawings for construction.
- A lack of clarity and confusing information in the construction drawing (Rec. 621915) also resulted in the misreading of the tower design drawing³⁹. This is caused by the use of legacy drawings (dating from the 1960's). The legacy tower drawings may not reflect the current needs of crews who perform the tower installations on an infrequent basis. The lack of drawing clarity results from

³⁸ Interview with crew foreman and crew lead

³⁹ Exponent reviewed drawings for various tower designs and there was a great variance in drawing clarity and how information was conveyed on the drawings related to heel and face batter. These variances indicate the potential for more formal training relative to construction review and understanding of the design drawings.

inadequate maintenance and updated drawings to factor in the current needs of the construction crews.

- The limited interface between engineering and construction contributed to the incorrect stub angle batter not being successfully transferred to the crew performing the construction. Given the criticality of this parameter and the presence of potential barriers, such as clarity and familiarity, which affect the ability of the message being successfully received, feedback is a reasonable way to assure the desired communication has taken place. Structured dialogue between engineering and construction provides an opportunity to reinforce training in reading and interpreting drawings, as well as for independent verification of the drawing information to the construction effort. The absence of robust training verification and documentation is caused by inadequate program design to identify the need for independent verification of the dimensions taken from the design drawings.

The second causal chain for the insufficient review of the job package relates to no requirement for an independent verification of the footing and stub angle settings relative to the design requirements. This is caused by the lack of procedures for an independent verification of the critical dimensions. This check is also not included in the template setting manual. The lack of the procedures is caused by inadequate program design to identify the need for independent verification of the dimensions taken from the design drawings.

2. There was no identification by the crew of potential misalignment issues with the tower. There was no evidence in documents or interviews with the crew that indicated that anything out-of-the-normal occurred during the construction and installation process. This was caused by the lack of guidance provided to the construction crew on tolerances for the tower design and issues to be observed during the construction process. This is caused by a further lack of guidance on when engineering needs to be contacted regarding field issues. This lack of guidance is caused by the lack of formal training for the construction crews on the overall design basis of the towers, as previously described.

6.2 Root and Contributing Causes

This section provides the results of the causal analysis to identify the root causes of the incident. Appendix E provides the evaluation of the causes identified in Section 6.1 to determine the root cause of the incident. The determination of the root causes is based on evaluating the causes at the ends of the causal chains, and determining whether these would have prevented or significantly reduced the probability of the incident, and whether they are under the control of management.

Based on the problem statement and the evaluation in Appendix E, the root cause of the incident is:

- ***RC1: Inadequate process to ensure that critical parameters (dimensions and/or steps) of the transmission towers are constructed as designed:*** The predefined verification methodology to ensure that design information from the tower drawings is correctly transferred to the construction installation process should be improved. There is no formal requirement to verify the take-offs from the drawings. Since the stub angle inclination is a key dimension for validating the tower design, a defined means to determine and confirm this dimension is required.

The determination of the contributing causes is based on evaluating the causes at the ends of the causal chains, determining whether these would have helped to reduce the probability of the incident, and whether they are under the control of management. Based on the problem statement and the evaluation in Appendix E, the contributing causes of the incident are:

- ***CC1: Inadequate process design relative to training requirements for tower drawings for transfer of design-related information to the construction crews:*** The tower construction utilizes general drawings and not site specific drawings. There is no formal training that provides the construction crew with information on what drawings to review and how to interpret these drawings. Also, the key parameters that govern the design are not communicated, except through informal on-the-job training. Additionally, there is a need for the crew foreman to perform a significant number of calculations on-site to transfer the design information to the field. Formal training provides a basis for understanding requirements, and gaining necessary information on significant design considerations, as impacted by construction activities. Also, tower erection is not performed frequently and the use of OJT exclusively may no longer be sufficient.
- ***CC2: Inadequate maintenance (update) of drawings relative to legacy tower drawings may not reflect the current needs of crews who perform the tower installations on an infrequent basis:*** The tower drawings are very dated and last updated in the 1960's. Therefore, this causes potential error in reading the drawings due to legibility issues, as well as missing or confusing information.
- ***CC3: Inadequate process design relative to training requirements for tower drawings on dimensional tolerances and potential field issues:*** This cause is similar to CC1 except that it relates to the field identification of potential issues. There is no formal guidance provided to the crews relative to fit-up tolerances on critical dimensional measurements and other field observations that may indicate a problem.

7. Recommended Corrective Actions

The desired outcome of a root cause analysis is to identify corrective actions to prevent recurrence of the problem. Effective corrective actions are those that address the root cause, are implementable by the organization, are cost effective, and are consistent with company business goals and strategies.

The recommended corrective actions from the causal analysis are defined for application by PG&E in processes that they control. Based on the root and contributing causes, the following actions are recommended to prevent recurrence of the problem are listed in Table 1:

Table 1. Recommended Corrective Actions

| Cause | Recommended Corrective Action |
|--|--|
| RC1: Inadequate process to ensure that critical parameters (dimensions and/or steps) of the transmission towers are constructed as designed | Develop and incorporate a formal and independent verification process for confirming stub angle inclination and other critical tower parameters into the tower construction effort. |
| CC1: Inadequate process design relative to training requirements for tower drawings for transfer of design-related information to the construction crews | <p>Develop a formal training program for tower design, including review of critical design and dimensional features and identification of potential issues during construction. This action is intended to ensure that design integrity is captured in the construction effort.</p> <p>Develop a more formal training program associated with the template setting manual</p> <p>Incorporate the template setting manual as a “PG&E standard” document</p> <p>Perform process safety analysis to identify critical design and construction activities related to tower design and construction; and identify appropriate actions</p> |
| CC2: Inadequate maintenance (update) of drawings relative to legacy tower drawings may not reflect the current needs of crews who perform the tower installations on an infrequent basis | <p>Update tower drawings to ensure legibility and more accurate information (especially related to stub angle measurements)</p> <p>Evaluate the need to create project specific drawings relative to current generic drawing approach</p> |
| CC3: Inadequate process design relative to training requirements for tower drawings on dimensional tolerances and potential field issue | See CC1 recommended actions |

8. Extent of Condition

The causal investigation focused on the specific incident only; and the evaluation of extent of condition issues were undertaken as a separate effort by PG&E. For this incident, the extent of condition issues relate to the stub angle placement for the larger towers. PG&E has undertaken a review of the 36 towers constructed over the past two years that utilized tower designs incorporating stub angle foundations. Based on this review⁴⁰, all of these tower stub angles were installed correctly with no signs of stress. Therefore, there are no further actions required for the evaluation of extent of condition.

⁴⁰ Reference 11: PG&E tower review file

9. Conclusions

The objectives of this root cause analysis were to determine the root and contributing causes and define the actions to prevent recurrence. From the findings identified, the tower collapse event was initiated by the incorrect settings of the stub angle due to a human error in determining the drawing heel batter; and the subsequent communication of this incorrect heel batter to the crew for use in setting the stub angles. Typical human error defenses (barriers to prevent human error) include training, procedures, clear documents and communication, and independent verification. Since the human error relative to the stub angle alignment with the tower legs resulted in a significant occurrence, the causal analysis includes a review of these barriers and their performance and contribution to the incident.

Based on the causal evaluation, the root and contributing causes of the incident are listed below:

- *Root Cause: Inadequate process to ensure that critical parameters (dimensions and/or steps) of the transmission towers are constructed as designed:* The verification methodology to ensure that design information from the tower drawings is correctly transferred to the construction installation process should be improved. There is no formal requirement to verify the take-offs from the drawings.
- *Contributing Cause 1: Inadequate process design relative to training requirements for tower drawings for transfer of design-related information to the construction crews:* The tower construction utilizes general drawings and not site specific drawings. There is no formal training that provides the construction crew with information on what drawings to review and how to interpret these drawings. Also, the key parameters that govern the design are not communicated except through informal on-the-job (OJT) training.
- *Contributing Cause 2: Inadequate maintenance (update) of drawings relative to legacy tower drawings may not reflect the current needs of crews who perform the tower installations on an infrequent basis:* The tower drawings are very dated and last updated in the 1960's. Therefore, this causes the potential for error in reading the drawings due to legibility issues, as well as missing or confusing information.
- *Contributing Cause 3: Inadequate process design relative to training requirements for tower drawings on dimensional tolerances and potential field issues:* This cause is similar to Contributing Cause 1, except that it relates to the field identification of potential issues. There is no formal guidance provided to the crews relative to fit-up tolerances on critical dimensional measurements, and other field observations that may indicate a problem.

Recommended corrective actions are identified and included in Section 7. The extent of condition was performed by PG&E and indicated no other towers were constructed within correct stub angle batter over the past two years as described in Section 8.

10. References

1. “Moss Landing Tower Collapse Analysis”; Exponent, Inc., dated December 18, 2015.
2. “Job Package: Moss Landing 230/115 kV BAAH Project Phase 2 Construction Binder”; Black & Veatch
3. “As-Built Mark-Ups”; prepared by [REDACTED] (PG&E)
4. Template Setters Training Manual
5. Structural Data Sheet 233101
6. Structural Drawing 403912
7. Foundation drawing 309933
8. Drawing 313438
9. Drawing: Rec. 621915
10. Interview Notes Summary from [REDACTED]
11. Review file: Moss_Landing_CA_Tower_Inspections.xlsx
12. US Department of Energy, Human Performance Handbook, Human Performance Improvement Concepts and Principles, 2007
13. Bea, R.G. Human & Organizational Factors: Quality & Reliability of Engineered Systems, Volume 1. 2008

Appendix A

Interview List

Interview List

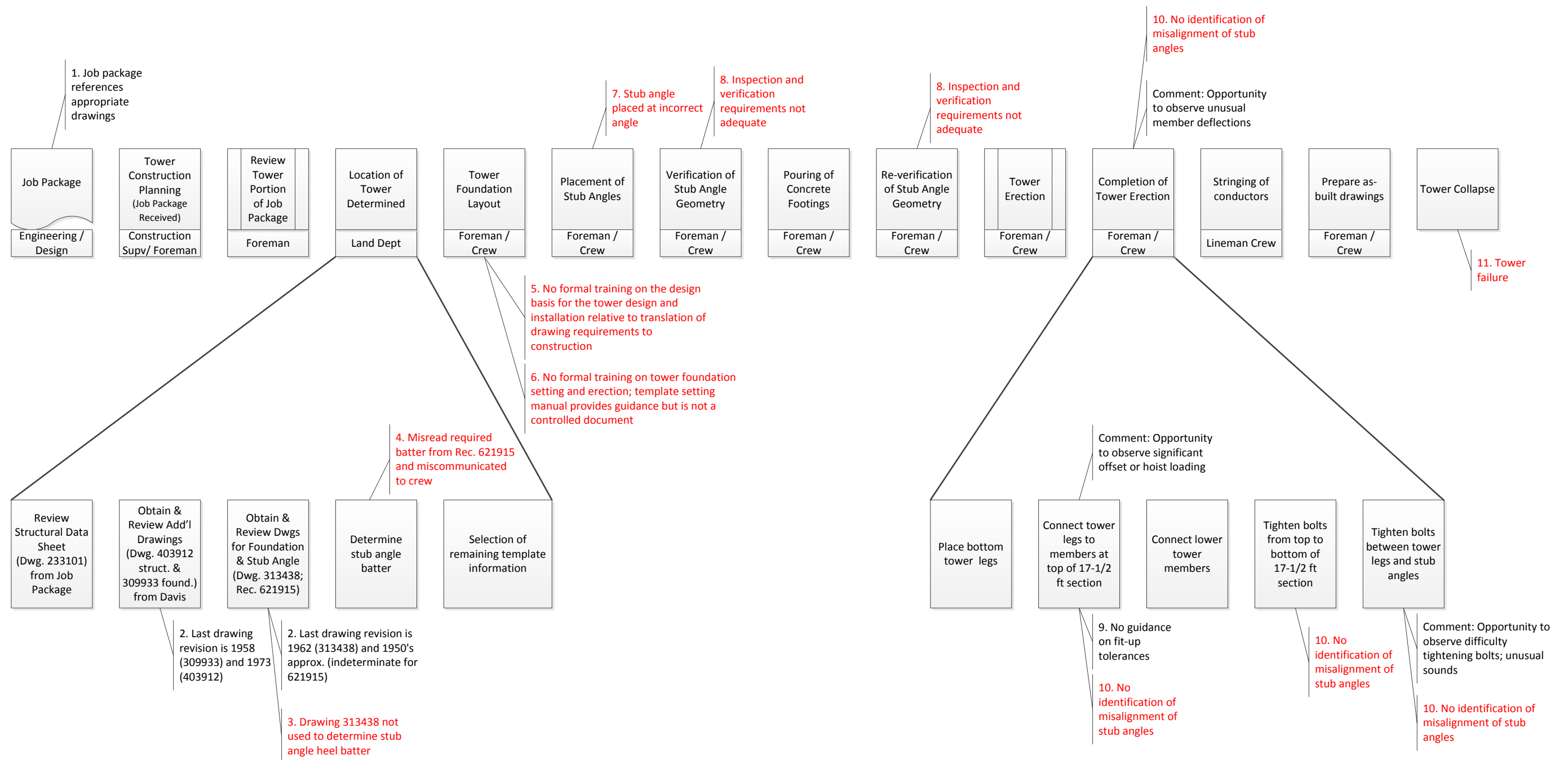
| No. | Employee Name | Title / Role | Date |
|-----|----------------|---------------------------------------|---------------------------------|
| 1 | [REDACTED] | PG&E Crew Foreman | February 25, 2016 ⁴¹ |
| 2 | [REDACTED] | PG&E Crew Lead | February 25, 2016 |
| 3 | [REDACTED] | PG&E Project Engineer | February 10, 2016 |
| 4 | [REDACTED] | PG&E Subject Matter Expert | February 5, 2016 ⁴² |
| 5 | Brian McDonald | Exponent Failure Analysis Lead | February 3, 2016 |
| 6 | Brad James | Exponent Failure Analysis - Materials | February 3, 2016 |

⁴¹ Additional discussions at stub angle installation demonstration at PG&E Livermore Facility on February 24, 2016

⁴² PG&E conducted interviews with selected crew members in mid to late December 2015 in preparation of root cause analysis

Appendix B

Event Timeline and Process Comparison



Notes

1. Numbered comments in “red” represent findings that will be used in the causal analysis.
2. Numbered comments in “black” represent observations that are consistent with requirements and expectations.
3. Un-numbered comments are for information only.

Appendix C

Findings Description and Evidence

| Note | Finding / Observation (Findings will be used in causal analysis; observations confirm that requirements and expectations were satisfied) | Finding / Observation Description | Evidence (Physical Evidence, Documents or Calculations) | Interviews | SME Input | Comment |
|------|---|--|--|--|--|---------|
| 1 | (Observation) Job package references appropriate drawings | The job package submitted to construction referenced the appropriate design drawings for the foundations and stub angles for the G95 tower. Note that not all drawings were included in the actual job package, but drawings are known and available to construction staff. | The following data sheet and drawings were reviewed for applicability to the tower design: Structural data sheet 233101; Structural drawing 403912; Foundation drawing 309933; and Drawing 313438; Rec. 621915 | Project Engineer confirmed reference drawings were applicable to the tower design. Construction staff indicated they were able to access standard drawings referenced by the design package. | Standards engineer confirmed reference drawings were applicable to the tower design | N.A. |
| 2 | (Observation) Drawing Age | The drawings for the G95 tower are unchanged over the past 50 years and drawings have issues with legibility in the field. | The copies of drawings included in the job package have legibility issues. | Crew foreman indicated drawing legibility is poor and there is a need to go back to original drawings to verify some of the drawing information. | Standards engineer indicated drawing legibility is poor and there is a need to go back to original drawings to verify some of the drawing information. | N.A. |
| 3 | (Finding) Drawing 313438 not used to determine stub angle heel batter | The structural data sheet references structural drawing 403912 for the G95 tower. This drawing and the structural data sheet references drawing 309933 for the foundations. This drawing references drawing 313438 and Rec. 621915 for additional foundation and stub angle details. The correct heel batter is indicated in Section C-C of drawing 313438. The heel batter is indicated as 2-5/8" per 12". | Drawing 313438 clearly shows a heel batter of 2-5/8" for G9-3 footing. | Crew foreman indicated that he used Rec. 621915 to determine the stub angle heel batter and that drawing 313438 was not relied upon for this information. | N.A. | N.A. |
| 4 | (Finding) Misread required batter from Rec. 621915 | Rec. 621915 is provided for additional foundation and stub angle details. The correct heel batter is indicated in Section C-C of drawing 313438 and also in the diagram in the top right of Rec. 621915. The heel batter is indicated as 2-5/8" per 12". The foreman indicated that the he communicated the incorrect heel batter, which led to the incorrect stub angle placement (see Note 8 later in this table). | The physical evidence from the field inspection and measurements after the tower collapse showed that 3 stub angles were placed at 1-5/8" per 12" while the fourth was placed at 1-3/4" per 12". | Interview with crew foreman indicates that the incorrect heel batter was communicated to the remainder of the crew. | N.A. | N.A. |

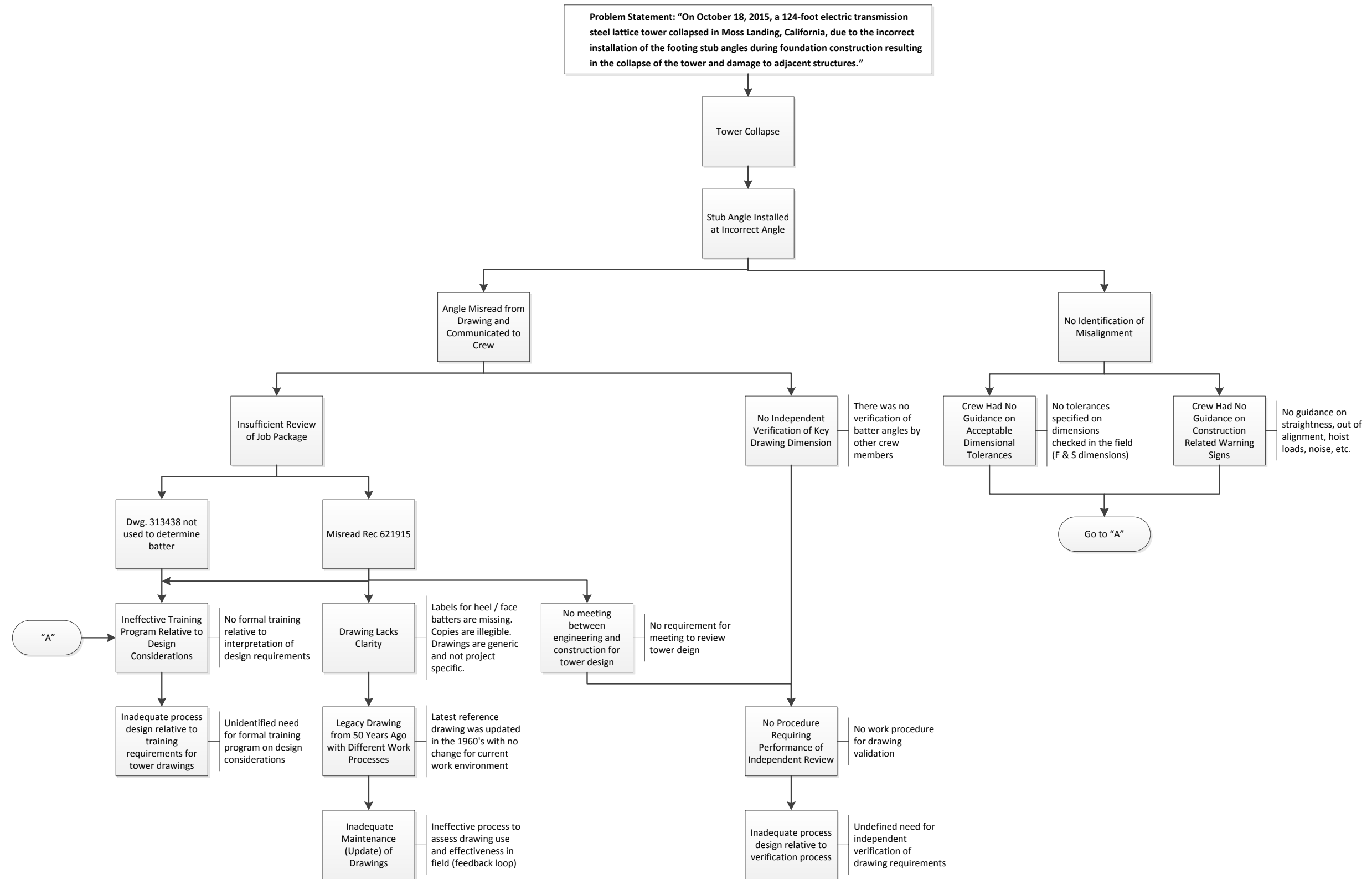
| Note | Finding / Observation (Findings will be used in causal analysis; observations confirm that requirements and expectations were satisfied) | Finding / Observation Description | Evidence (Physical Evidence, Documents or Calculations) | Interviews | SME Input | Comment |
|------|--|--|---|---|--|---------|
| 5 | (Finding) No formal training on the design basis for the tower design and installation relative to translation of drawing requirements to construction | There are no formal procedures or training provided on the basis of the tower design; interpretation of the tower design drawings; and identification of potential issues requiring engineering review (such as dimensional discrepancies). | There is currently no training provided to construction on the basis of the tower design and erection | Interviews with crew and engineering personnel confirmed that no formal procedures or training is provided. | Standard engineer confirmed that no formal procedures or training is provided. | N.A. |
| 6 | (Finding) No formal training on tower foundation setting and erection; template setting manual provides guidance but is not a controlled document | There are no formal procedures or training for tower foundation setting and erection. There is reliance for on-the-job training and guidance from a template setting manual. Additionally, the template setting manual is not a controlled document and has limited distribution to the crews (mostly resides with supervisors and foreman). | The setting template manual has been reviewed and there is no control of this document. | Interviews with crew and engineering personnel confirmed that no formal procedures or training is provided. | Standard engineer confirmed that no formal procedures or training is provided. | N.A. |
| 7 | (Finding) Stub angle placed at incorrect angle | Three stub angles were placed at 1-5/8" per 12" and the fourth was placed at 1-3/4" per 12" vs. the required 2-5/8" per 12". | The physical evidence from the field inspection and measurements after the tower collapse showed that three stub angles were placed at 1-5/8" per 12" and the fourth was placed at 1-3/4" per 12". | Project Engineer confirmed correct batter for this installation as 2-5/8" per 12". | Standards Engineer confirmed correct batter for this installation as 2-5/8" per 12". | N.A. |
| 8 | (Finding) Inspection and verification requirements not adequate (pre-concrete pour and post-concrete pour) | There are no requirements established for independent verification activities for determination of dimensions from the tower drawings. There was no verification of the stub angle batter for this tower erection against the drawing requirements. Additionally, there is no guidance provided for dimensional tolerances (e.g. dimensions F and S "to theoretical heel of top of stub", see drawing 313438). | The physical evidence from the field inspection and measurements after the tower collapse showed that three stub angles were placed at 1-5/8" per 12" and the fourth was placed at 1-3/4" per 12" instead of required 2-5/8" per 12". The verification process was not effective. | Crew lead indicated that he did not check the stub angle requirement. Stub angle batter was communicated by crew foreman. | N.A. | N.A. |

| Note | Finding / Observation (Findings will be used in causal analysis; observations confirm that requirements and expectations were satisfied) | Finding / Observation Description | Evidence (Physical Evidence, Documents or Calculations) | Interviews | SME Input | Comment |
|------|---|---|--|--|-----------|--|
| 9 | (Finding) No guidance on fit-up tolerances | There are no tolerances indicated on the tower, foundation and stub angle drawings related to placement of the stub angles and fit up of the bottom portion of the tower. Therefore, there is no guidance provided to identify potential fit-up issues. | There are no tolerances shown on the tower drawings. | Engineering indicated that they did not provide fit up tolerances to Construction. Engineering indicated that the intent was to have the stub angles at the specified batter and that the tower calculations were based on this batter with no tolerance specified or allowed. Crew foreman indicated that there is no guidance for fit up tolerance | N.A. | The lower tower is erected with members loosely bolted as the structural braces and cross members are attached. The bolts are then tightened (typically) from the top down to the leg – stub angle bolts. The 17-1/2 ft. distance may not allow for visual identification of fit-up problems or alignment problems due to the stub angles. |

| Note | Finding / Observation (Findings will be used in causal analysis; observations confirm that requirements and expectations were satisfied) | Finding / Observation Description | Evidence (Physical Evidence, Documents or Calculations) | Interviews | SME Input | Comment |
|------|--|--|--|---|-----------|---------|
| 10 | (Finding) No identification of misalignment of stub angles (during fit-up at top of 17-1/2 ft. legs, during installation of bracing, and during bolt tightening) | There was no identification of the stub angle inclination error during the tower installation. | N.A. | Crew foreman and lead indicated that there was no identification of stub angle batter error during the tower erection process. Crew foreman and lead indicated that tower fit-up appeared to be normal and similar to other towers. There was no recognition of potential issues due to load on hoist, offset at top of legs, or any noises or issues with tightening of bolts between legs and stub angle. | N.A. | N.A. |
| 11 | (Finding) Tower collapse | The tower collapsed on October 18, 2015 and caused damage to an adjacent tower. This is the failure event. | Failure analysis report (Ref. 1) indicated that tower collapse was caused by the incorrect stub angle setting (incorrect heel batter) that led to higher than designed stub angle stresses and also by stub angle material with insufficient fracture toughness. | N.A. | N.A. | N.A. |

Appendix D

Event and Causal Factors Chart



Appendix E

Causal Factors Analysis Chart

Causal Factor Analysis

| | | | | |
|--|---|--|---|--|
| <p style="text-align: center;">Problem Statement</p> | <p><u>Problem Statement</u> On October 18, 2015, a 124-foot electric transmission steel lattice tower collapsed in Moss Landing, California, due to the incorrect installation of the footing stub angles during foundation construction resulting in the collapse of the tower and damage to adjacent structures..</p> | | | |
| <p style="text-align: center;">Cause(s)</p> | <p>Inadequate process design relative to training requirements for tower drawings for transfer of design-related information to the construction crews</p> | <p>Inadequate maintenance (update) of drawings relative to legacy tower drawings may not reflect the current needs of crews who perform the tower installations on an infrequent basis</p> | <p>Inadequate process to ensure that critical parameters (dimensions and/or steps) of the transmission towers are constructed as designed</p> | <p>Inadequate process design relative to training requirements for tower drawings on dimensional tolerances and potential field issues</p> |
| <p style="text-align: center;">Criteria 1 (within organization's control to fix)</p> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Yes</div> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Yes</div> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Yes</div> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Yes</div> |
| <p style="text-align: center;">Criteria 2 (likelihood the incident or condition would be prevented if removed)</p> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Medium</div> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Medium</div> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">High</div> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Medium</div> |
| <p style="text-align: center;">Type of Cause</p> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Contributing Cause</div> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Contributing Cause</div> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Root Cause</div> | <div style="border: 1px solid black; padding: 5px; width: 60px; margin: 0 auto;">Contributing Cause</div> |