HEAVY MOVABLE STRUCTURES, INC.

NINTH BIENNIAL SYMPOSIUM
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SAN FRANCISCO CABLE CAR TURNTABLE REHABILITATION – THE LITTLE SWING BRIDGE

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MACHINERY/MECHANISMS

Introduction

The driving force behind the San Francisco cable car system came from a man who had witnessed a horrible accident on a typically damp summer day in 1869. Andrew Smith Hallidie saw the toll slippery grades could extract, when a horse drawn streetcar slid backwards under a heavy load. The steep slope with cobblestones and a heavy weighted vehicle, combined to drag five horses to their deaths. Although such this event would stun anyone, Hallidie and his partners had the know how to do something about the problem.

Hallidie was born in England and moved to the U.S. in 1852. His father filed the first patent in Great Britain for the manufacture of wire ropes. As a young man, Hallidie found uses for this technology in California's gold country. He used the wire rope when designing and building a suspension bridge across Sacramento's American River. He also found another use for the wire rope in pulling heavy ore cars out of underground mines on tracks. Therefore, technology was in place for pulling cable cars.

The next step to bring Hallidie closer to his fate was in moving his wire rope manufacturing business to San Francisco. The seeds had been sewn for making a full-blown cable car railway system to deal with San Francisco's fearsome hills a reality.

Currently, as part of the San Francisco Municipal Railroad (MUNI), the cable cars are solid revenue generators used by both residents and tourists, with annual rider ship exceeding ten million.

The cable car turntables, at the end of each of the three operating lines, Powell/Mason, Powell/Hyde and California, is a 19-foot steel structure with a wooden deck and a dead load of 30,000 lbs (similar to a small manually operated swing bridge). The car operator manually turns each cable car at the end of each run. After decades of operation, the turntables had become difficult to operate due to wear of the supporting components. In 2001, a decision was made to rehabilitate the turntables at Hyde and Powell Streets to improve the operational performance.

Parsons Brinckerhoff Quade & Douglas, Inc, (PB) was retained by MUNI's, Cable Car Maintenance Division to perform design analysis of proposed modifications. The MUNI engineering staff prepared the rehabilitation design.

This paper describes the background of the rehabilitation alternatives considered and eventually implemented. The first phase of the rehabilitation, at the intersection of Beach and Hyde Streets, was completed in June 2001.

System Description

San Francisco's cable cars are unique in that they are the only street railways in which the cars do not operate under their own power. Instead the cars are propelled mechanically by "gripping" a continuously moving steel cable that runs in a conduit underneath a slot between the rails. There are four continuous cables for the three lines. The cable, 1 ¼-inches diameter consists of six steel strands of 19 wires, each wrapped around a sisal rope core. The cable in turn is kept in constant motion by an engine in a centrally located powerhouse at Washington and Mason Streets. Each cable in the powerhouse has its own drive machinery: a 510-horsepower DC electric motor and gears to reduce the speed of the motor to the proper cable speed of 9-¼ mph. To keep the cable from slipping when powered, each cable wraps around its powered driving sheave, under and over an unpowered idler sheave.

Design Overview

The Beach & Hyde Street turntable, a nineteen-foot diameter steel structure with a wooden deck, has a single inbound and outbound track that run to and from the center of the turntable (Photo 1). The turntable's dead load - 30,000 lbs and maximum cable car weight, 16,000 lbs -is transferred to a concrete pier through a cylindrical steel pedestal. Six roller bearings are bolted to the top of the base plate (Photo 4).

To stabilize the turntable during rotation on the roller bearings, a 4-inch pin connects the steel support to the turntable. Four balance rollers running on a curved rail provide additional support from tipping when the front wheels of the cable car enter the turntable platform. The balance wheels ride on single curved rail.

Design Modification

The design modification intent was to reduce the rotating torque by reducing the friction between the turntable and the supports by incorporating a 50.625 -inches diameter angular contact thrust bearing. The selected bearing, with a static capacity of 2,231,000 lbs, has forty-one 3-inch diameter ball bearings. The upper race of the bearing directly supports the turntable by means of an upper adapter ring plate. The adapter ring plate is bolted to the base of the turntable (see figure 1).

The design drawings, specifications and construction sequences were prepared by MUNI's staff engineers. PB's role were as follows:

- Evaluating on the proposed design of the turntable modifications.
- Assessing the adequacy of the design for meeting the performance improvements from an operations and maintenance perspective.
- Evaluating the constructibility of the proposed design modifications

The following issues were of particular concern to the client.

- Keeping the lubricant sealed within the bearing races.
- The frictional torque capacity of the lower and upper bearing race surfaces to keep the bearings from slipping on the bearing pedestal base.
- The ability of the proposed modification to achieve the designed static frictional torque of less than 40lbs.

The design review scope specifically listed the following items to be addressed:

1. Evaluating the usefulness of leaving the original 4 inch diameter center pin in the modified turntable mechanism versus removing it from the modified mechanism
2. Checking design calculations and assumptions on the static and dynamic friction and turning forces required for the new turntable assembly.
3. Evaluating the tipping moment and impact stresses on the ball bearing
4. Developing and implement a testing procedure to evaluate the forces needed to turn the Cable Car turntable. The procedure should provide us with consistent data that can be used to evaluate the ergonomic performance of the turntable.
5. Developing a list of recommendations and design changes to minimize corrosion and contamination of the mechanism and structure of the turntable.
6. Evaluating the general effectiveness and constructibility of the turntable modifications.

4-Inch Diameter Center Pin

The design eliminated the use of 4-inch diameter center pin. Friction between the turntable and the support component will be reduced. Calculations were performed to predict the stability of turntable when subjected to the service loads, since loading condition B1 and D are the worst cases, calculations were performed for each of the conditions. The evaluation indicated that that the turntable would not tip under the maximum service loads.

Evaluation of Design Calculations

Contact Stresses

The Torrington Company performed an analysis to determine if the selected bearing (Torrington 0-1596-A) could adequately support the service loads. In order to model the service loads, five loading conditions were evaluated. The contact stresses for these loads were evaluated. Based on conversations with Torrington engineers, the analysis was carried out using sophisticated proprietary computer software. Torrington found that the worst-case loading was the loading condition they had named condition D.

As the car rolls onto the turntable, loading condition D occurs at the instant the second pair of wheels bears onto the turntable. Since it is assumed that the total car load is distributed evenly between each wheel, load condition D is expressed as two 4 000 pound point loads at distances of 50.5 and 113.5 inches from the turntable's centerline (See the appendix for a figure showing the position of the car for load condition D). The contact stress for this loading condition is 380ksi. According to Torrington, this stress is within the allowable of 480 ksi for the bearing ball material (AISI 52100).

Torrington's calculations were reviewed by re-calculating the bearing contact stress by-hand. Since this is a lengthy calculation, the hand calculation was limited to only the worst-case loading condition (condition D). There were three steps to the hand calculation.

1. Find the maximum load that must be supported by a single ball. Since the car is evenly centered on the turntable for load condition D, the load is eccentric. The balls do not support the load evenly. Approximately, 3230 pounds was calculated as the maximum load that any individual ball must support.
2. Knowing the load and the contact area, contact stress may be calculated.

The above calculation resulted in a contact stress of 160 ksi.

The rollers and raceways were made of AISI 52100 alloy steel, which has an Ultimate Tensile Strength (UTS) ranging from 420 to 510 ksi (Harris, "Rolling Bearing Analysis" 4th Edition, pg 614) depending on the heat treatment. Torrington, the manufacturer of the bearings maintains an allowable contact stress of 480 ksi. However, both ISO and ANSI standards prove the concept that bearing components may support loads that result in permanent deformation, without effecting bearing performance. Therefore, the given bearing could actually sustain contact stresses of up to 609 ksi before performance is affected.

Given identical loading conditions, the hand calculation indicated a lower contact stress (160 ksi) when compared to Torrington's computer based analysis (380 ksi). This is to be expected for the following two reasons:

1. The hand calculation assumed that the contact angle (α) remained constant. In reality the contact angle would increase with the bearing load. As the contact angle increases, so does the contact force needed to support a given bearing load, due to "wedging action."
2. The hand calculation found the maximum stress at the interface between the roller and raceway. In reality, the maximum stress would not occur at the interface, but below the surface.

The hand calculation verified Torrington's conclusion that the 0-1596-A bearing would safely support the loading condition D, however, loading condition D ignores impact at the rail joint that can be substantial.

Bearing Friction Torque

Calculations were performed to predict the amount of friction torque the operator must overcome to rotate the turntable, once the Torrington 0-1596-A bearing is installed. The calculation involved four steps. First the friction internal to the bearing was calculated, using the bearing's load, capacity and geometry. Since the first step did not account for any friction due to the bearings seals, an assumption was made that the seals would cause the overall bearing friction to double. The second step was to account for friction in other components of the turntable assembly. This unknown was accounted for by assuming that the friction of the entire turntable assembly would be twice that of the overall bearing friction. Since the friction torques found in steps one and two were all dynamic, the final step was to find the static or starting friction of the turntable assembly. It is common for the static friction torque in rolling element bearing to be double the dynamic friction torque. Therefore, it was assumed that the starting torque to overcome the friction of the turntable assembly would be twice the dynamic friction torque of the turntable.

By taking the results for the turntable starting torque from step four above is was possible to determine the amount of force the operator must apply to begin the turntable and car rotating. Calculations prepared indicate that, an operator pushing on the handrail need not apply any more than forty pounds of force. The results were consistent with the calculations prepared by the Division and Torrington.

Corrosion of Turntable Component

The turntable steel members were corroded. Some of the steel members appeared to be corroded with section loss. Water seeping through the edges of the turntable pit had contributed to corrosion of the steel members.

The plans to rehabilitate the turntable included sand blasting and painting of the turntable steel structure. Since the plans did not include replacement of the turntable steel structure, the structure was thoroughly inspected after sandblasting. Steel members with section loss were strengthened or replaced.

Suggestions to provide a "skirt" around the steel structure within the pit were evaluated. The use of curved channels around the structure was evaluated. This recommendation did not appear practical, as this will not prevent seepage of water onto the turntable.

The Carboline Company was contacted. The company recommended a three coat painting system for this severely corrosive environment. For the initial base Carbothane 11- a zinc primer should be used. The intermediate coating should be with Carbomastic 15, an aluminum base coating. The final recommended coating is Carbothane 133HB.

Balance Rollers

The balance rollers located at the perimeter of the turntable help stabilizes the turntable on an outer rail during the movement of turntable. The gap between the rollers and the rail was more than an inch. The rehabilitation of the turntable did not include repairs to the rollers, as they appeared to be in good condition. However, we recommended that the roller supports be shimmed as part of the rehabilitation.

Design Recommendation

The turntable modifications design and the construction sequence was feasible. The calculations prepared were adequate for the level of performance. However, the angular thrust bearing has a finite life and would need an effective maintenance plan during it useful life. The following recommendations were made based on our evaluation.

1. Provisions should be made to replace or strengthen corroded steel members with sections loss.
2. Seals should be provided around the outer grease shield on the thrust bearings.

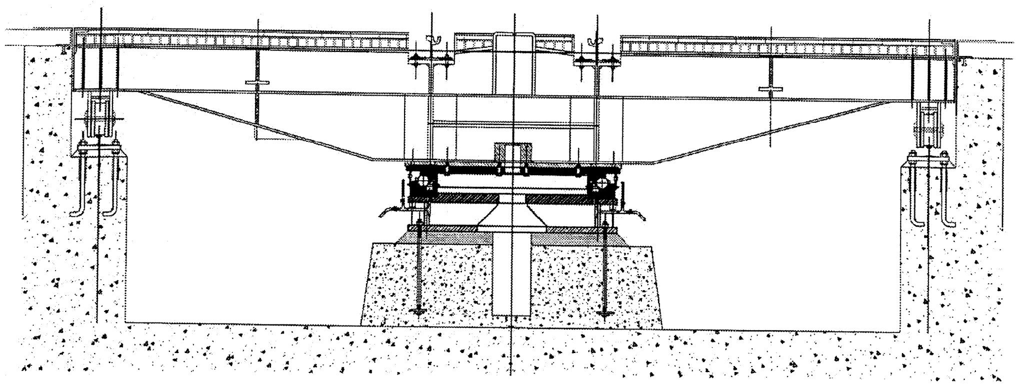
3. Shim the balance rollers to maintain a 1/16" gap. This requirement was critical to the stability of the turntable and thrust bearing due to the elimination of the 4" pin.
4. Calculations indicated that there would be no slippage between the bearing races. Conversations with Torrington engineers indicated that the shear pins were not needed, however, the lower pedestal plate should be machined to close tolerances and extremely flat surface.

Conclusion

The general arrangement of the Turntable and it's bearing can be directly related to a swing bridge. The design of movable bridges in the United States is governed by one of two codes, for highway bridges, the AASHTO Standard Specifications for Movable Highway Bridges, 2000; and for railway bridges the AREMA Manual, Chapter 16, Steel Structures, Part 6. Traditionally, swing bridges have utilized either bronze pivot bearings or steel conical roller bearing.
Angular contact thrust ball bearings are lately being proposed on several center bearing swing bridges in lieu of bronze discs. Whereas the use of the anti-friction bearing provides a low starting friction torque, these bearings normally have a finite life due to eventual failure by fatigue. Additionally, the bearings have several components that need to be maintained and have less capacity to withstand shock. Roller bearings need to be installed on extremely flat surfaces and to very close tolerances.

Journal bearings such as the bronze discs have been used on swing bridges for decades and can run "forever" after the initial installation.

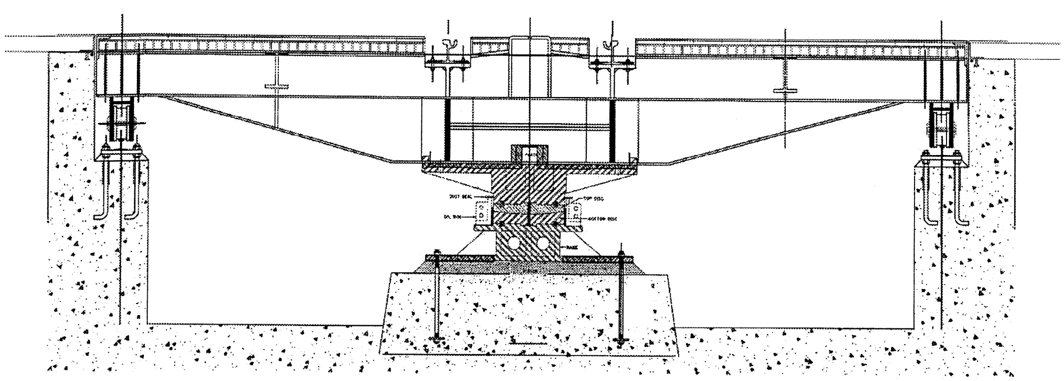
The two deferent systems have their clear advantages, however if and when an angular thrust bearing is used in lieu of the bronze discs, a careful evaluation of the bearing and all loading conditions should be conducted.



PROPOSED DESIGN

CABLE CAR SYSTEM
IMPROVEMENT TO TURNTABLE
HIDE AND BEACH STREET

FIGURE 1



ALTERNATIVE DESIGN

CABLE CR SYSTEM
IMPROVEMENT TO TURNTABLE
TURNTABLE ASSEMBLY

FIGURE 2

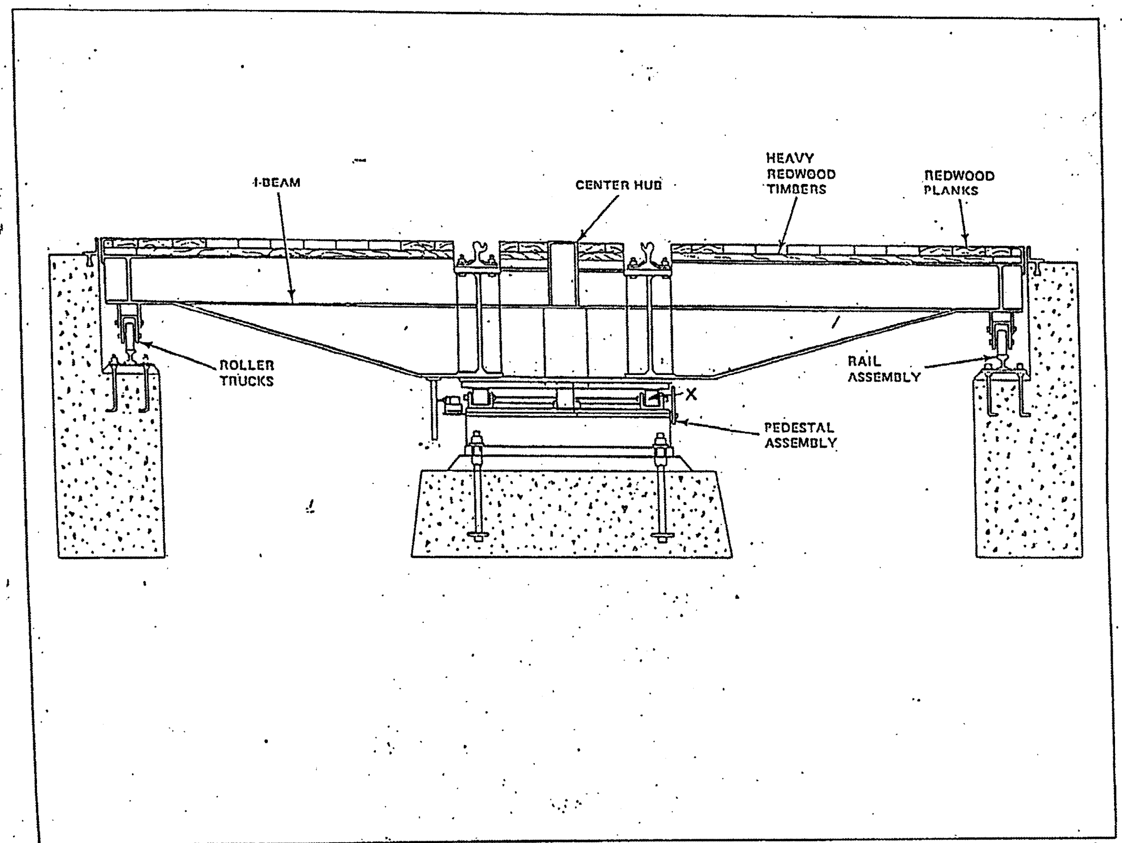


Figure: Turntable Structure (Typical) X: Rotating Components
1984 – Present

IR Torrington

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Mr. Mike Chan
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Subject: Torrington O-1596-A Thrust Bearing for Cable Car Turntable

Dear Mike:

We have reviewed the final data and drawings for this application that you faxed to Bill Wood of our San Francisco office on October 24th. We have shown several loading conditions below and the corresponding contact stresses induced. The following load data is used for calculations:

Turntable weight – 30,000 lbs.
Maximum car Weight – 16,000 lbs.
Table diameter – 18'-11" (227")
Vertical distance from top of table (rail) to bearing centerline – 37"
Impact loading produced by car's grip bar hitting rail = 20,000 lbs.

Condition A

Car is stationary and centered on the turntable.
Contact stress = 285 ksi

Condition B

First wheel of car moves 10" onto table (4,000 lbs. load @ 103.5" from C/L) and grip bar (10" behind) strikes rail. (Table)
Contact stress = 317 ksi

Condition B1

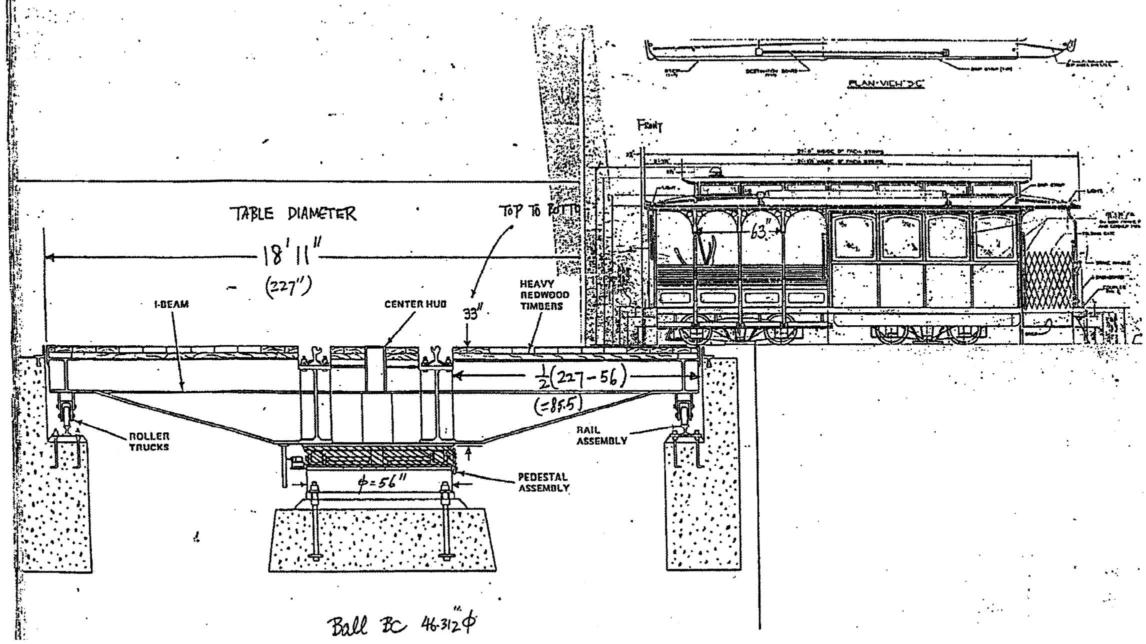
First wheel of car moves 20" onto table (4,000 lbs. load @ 93.5" from C/L) and grip bar (20" behind) strikes rail.
Contact stress = 363 ksi

Condition C Fig. A.

First wheel enters table and rail at 113.5" from table centerline.
Contact stress = 336 ksi

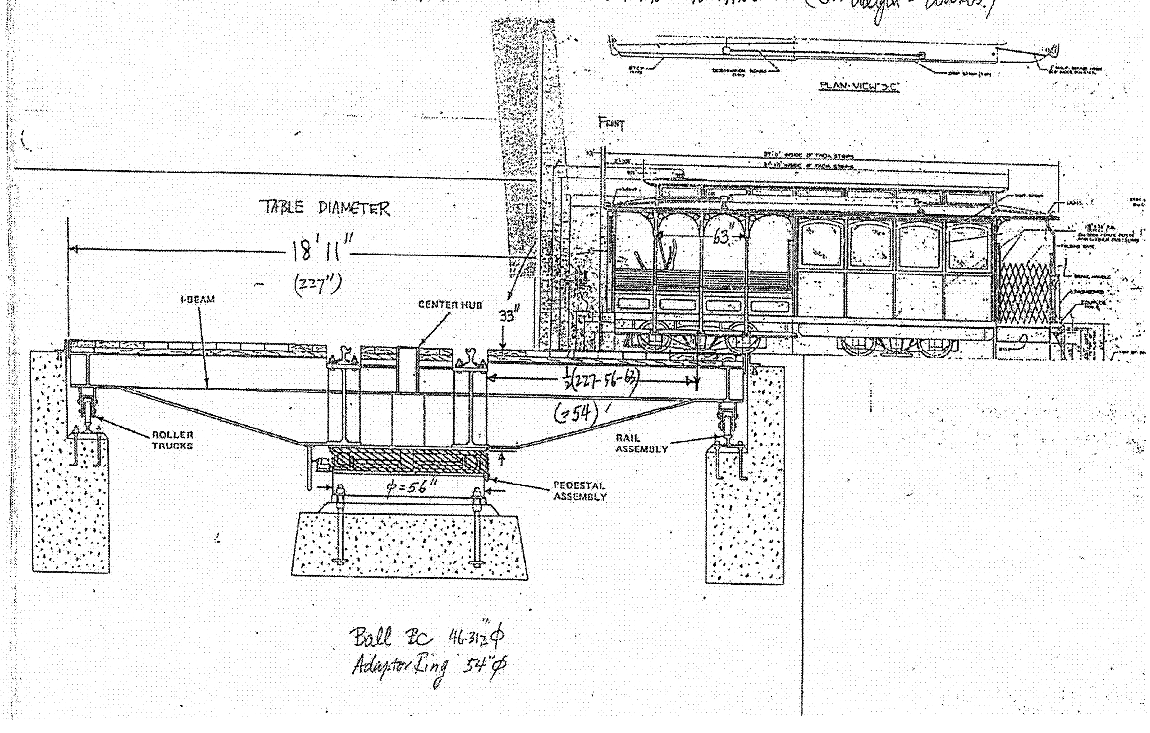
Condition D Fig. B.
First wheel moves 63" onto table (4,000 lbs. load @ 50.5" from C/L), second wheel enters at 113.5" from centerline (additional 4,000 lbs. load).
Contact stress = 376 ksi

FIG. A.: Front wheel inside turntable (Car Weight = 4000lbs.)



Ball BC 46.312"ϕ

FIG. B.: Front truck inside turntable (Car weight = 8000lbs.)



Ball BC 46.312"ϕ
Adaptor Ring 54"ϕ

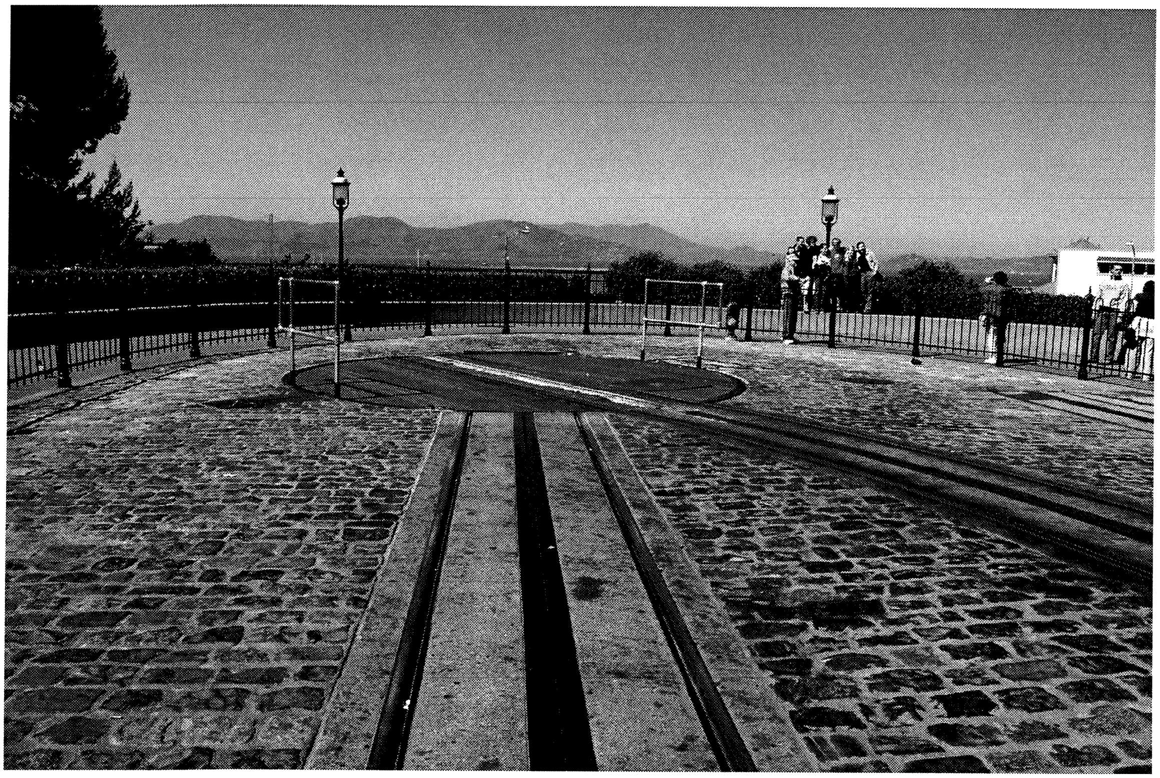


Photo 1- Existing Turntable at track level

Photo 2- General Elevation of Turntable Support

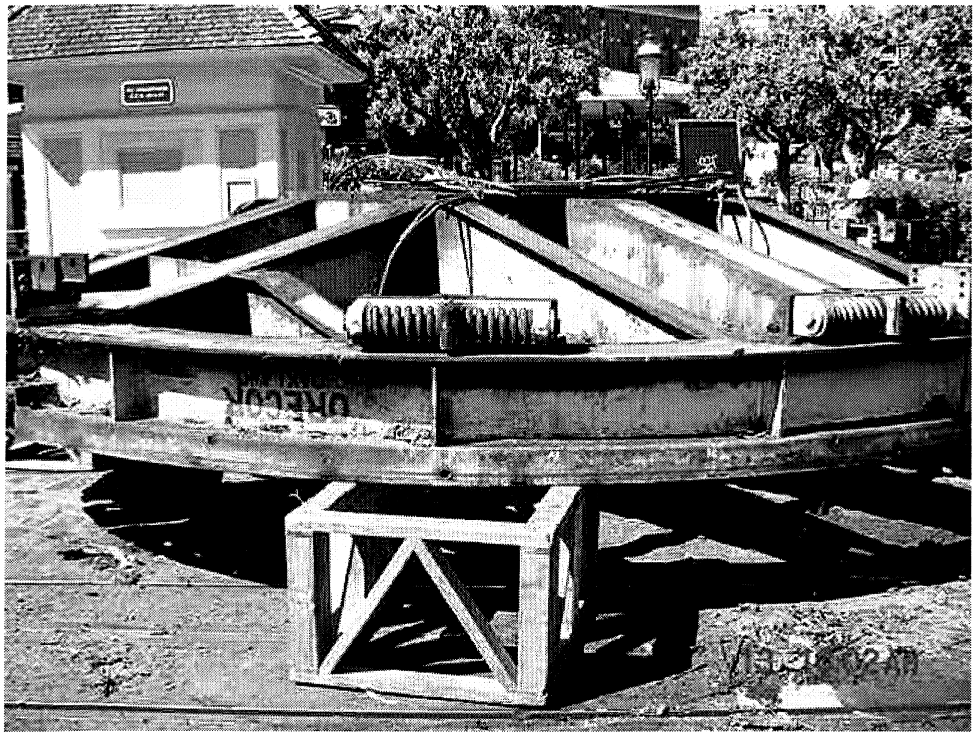


Photo 3 – Turntable removed from pit

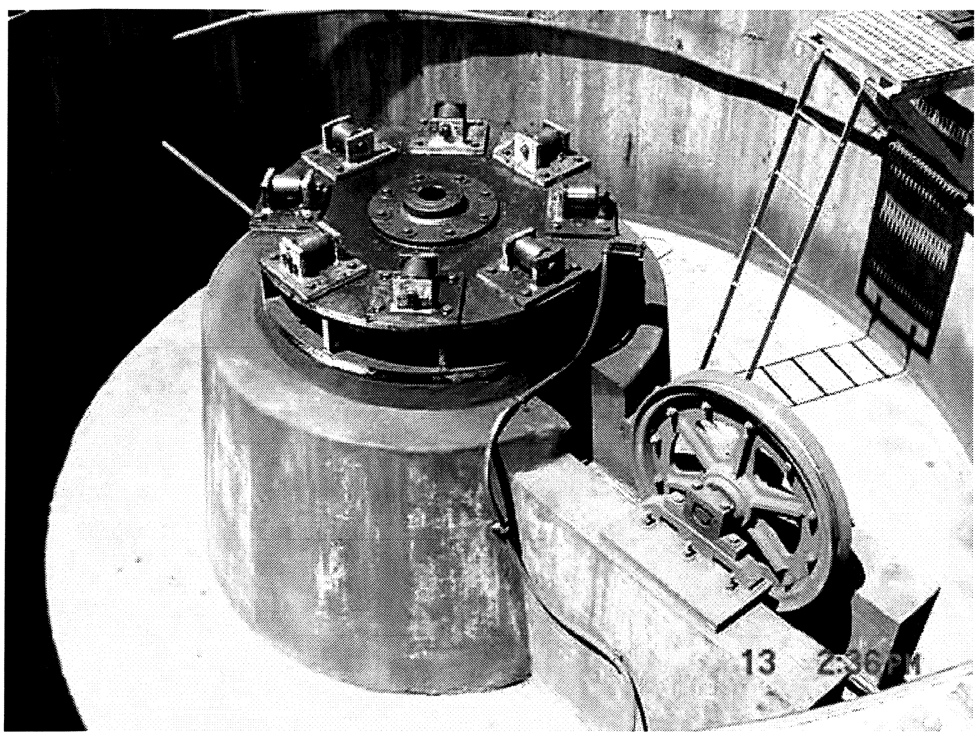


Photo 4- Turntable support Pedestal

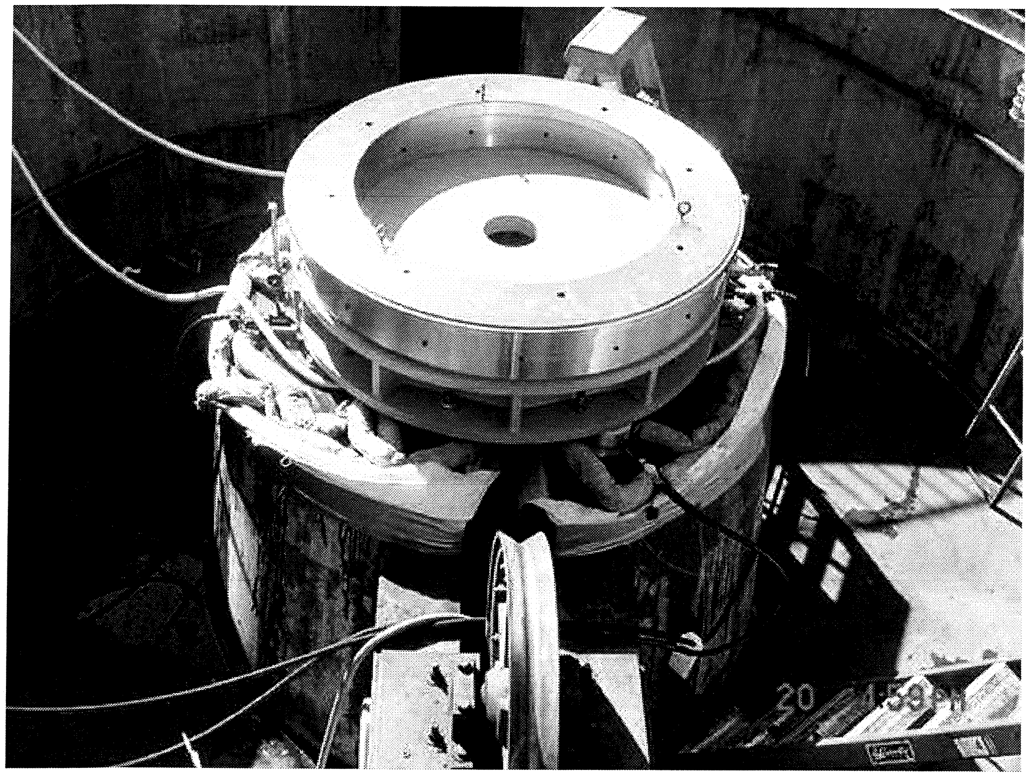


Photo 5 – New Trust bearing on pedestal

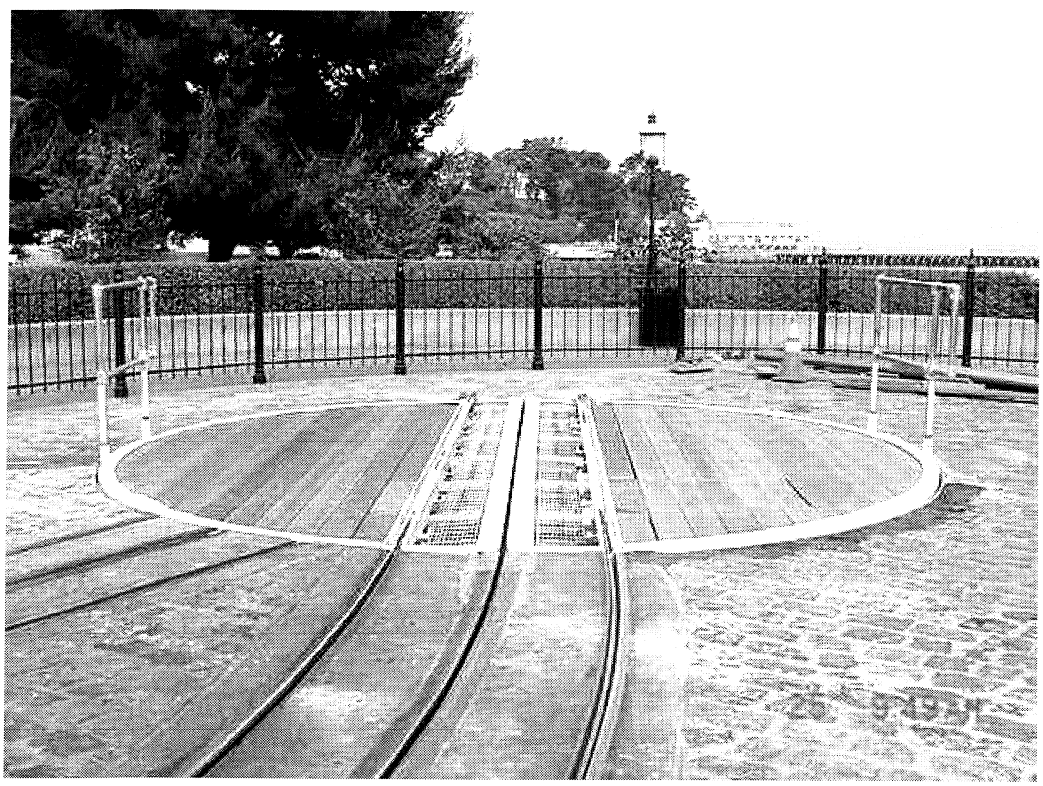


Photo 6 – Rehabilitated Turntable