

**FORENSIC INVESTIGATION OF THE FAILURE OF AN
INTERCEPTOR SEWER, SEA CLIFF AREA, SAN FRANCISCO,
CALIFORNIA**

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ABSTRACT

On December 11, 1995 a 100-year old brick interceptor sewer ruptured in the exclusive Sea Cliff area of San Francisco. The failure occurred during an intense, but not extraordinary, rainstorm. Storm water was constricted by a partly-lowered gate in an Overflow Structure that had recently been constructed some 1400 feet downstream of the failure. The constrictions caused pressurization of the sewer. At the site of the initial failure, water was forced through cracks in the sewer wall. Disturbance of the sand soil surrounding the brick sewer, caused by earlier excavation of an adit below and the development of a construction sinkhole, relaxed the soil confinement and allowed cracks to widen and water to escape that ultimately resulted in complete rupture of the sewer. Discharge from the sewer eroded a pit over 250 feet wide and 40 feet deep that caused the nationally-televised destruction of a historic home, as well as severe damage to adjacent public and private property. This paper is a summary of the public report of the forensic investigation and subsequent investigations.

KEYWORDS

Brick sewer, forensic investigation, interceptor sewer, sinkhole, San Francisco.

INTRODUCTION

In the early hours of the morning of December 11, 1995, during a series of events collectively referred to as the Sea Cliff Incident, storm water gushed from the failed 24th Avenue brick sewer located between 24th Avenue and El Camino del Mar in the exclusive Sea Cliff area of San Francisco ([Figure 1](#)). Discharge from the ruptured sewer scoured fine, uniformly graded dune sand. Scouring eventually created a pit over 250 feet wide and 40 feet deep that undermined the overlying Billman house and property, resulting in the “real-time” nationally-televised collapse and destruction of the Billman residence. Parts of neighboring residential properties, including property and garage of the Yee family ([Figure 2](#)), City of San Francisco streets and utilities, electrical and gas lines, and the Presidio National Park were also severely damaged. Sewage contaminated discharge eventually traveled over 1.5 miles through the newly constructed Richmond

Transport tunnel ([Figure 1](#)), and discharged across a major road and into the Pacific Ocean via the scenic Ocean Beach, part of the Golden Gate Recreation Area. Eventual claims against the City of San Francisco totaled several tens of millions of dollars.

The Department of Public Works of the City and County of San Francisco retained Exponent, Inc. (Exponent: then known as Failure Analysis Associates, Inc.) to perform an independent forensic investigation of the causes of the Sea Cliff Incident. The City and County of San Francisco publicly released the report of the independent forensic investigation in April, 1996 (Failure Analysis Associates, 1996; Medley and Delp, 1998). The City of San Francisco then retained Exponent as consultants to the Office of the City Attorney, to perform additional detailed analyses of the causes of the Sea Cliff Incident, and assist the City in litigation that followed the Incident.

This paper summarizes the principal findings from the forensic investigations.

DESCRIPTION OF SEA CLIFF AREA AND 24TH AVENUE BRICK SEWER

The Sea Cliff area ([Figure 1](#)) was developed in the 1920's and 1930's and is an architecturally distinctive and affluent neighborhood of San Francisco. The incident area is roughly bounded by Lobos Creek, El Camino del Mar, the Yee residence, and the northern end of 24th Avenue ([Figure 1](#)). Lobos Creek is confined by a steep bank to the south, a steep bank to the west (inclined at about 20 degrees and rising approximately 50 feet to the Billman property); and by an embankment supporting El Camino del Mar to the north. The creek flows northward through a culvert beneath the embankment. The surface soils of the incident area ([Figure 3](#)) are composed of loose to medium dense, fine and uniform sand fill (Unified Soils Classification of SP) and silty sand (SM) probably derived from the underlying native SP dune sand. The soil cover above the pipe within the incident area ranged from 5 to 15 feet ([Figure 3](#)) and elsewhere reached a maximum of about 45 feet ([Figure 11](#)).

The 24th Avenue circular brick sewer was constructed in the 1890's. The sewer passed beneath Presidio lands and the Billman property driveway, the latter being connected to both the 24th Avenue cul-de-sac and El Camino del Mar. The sewer was about located 15 feet below the ground surface at the garage of the Yee residence, and after making several turns ([Figure 1](#)), continued generally northwesterly to end at an outfall some 2000 feet downstream. The sewer conveyed dry-weather sanitary sewage and storm water runoff. Dry-weather sanitary sewage was routed from the Overflow Structure ([Figure 1](#)) at Sea Cliff Avenue to the nearby Sea Cliff Pump Station No. 2 at Sea Cliff Avenue, where sewage was pumped south, and eventually treated at the City's Oceanside waste water facilities. During rainfall events, storm flows bypassed the dry-weather diversions below the Sea Cliff Avenue Overflow Structure and discharged to the outfall at beach level north of Sea Cliff.

The sewer is six feet in internal diameter ([Figure 3](#)) and is formed of a 12-inch thickness of bricks laid in three courses. Several tens of feet upstream from the incident area, a 60-foot long concrete jacket was constructed in 1934 to repair a reported 45-foot long longitudinal split in the sewer ([Figure 5](#)). Sewage had leaked from the sewer and contaminated Lobos Creek, which was the source of potable water for the Sixth

Army, based at that time in the Presidio. Ground cover over the sewer was about 5 feet in the area of the repair, and was relatively shallow upstream of the failure, as indicated in [Figure 3](#).

CONSTRUCTION ACTIVITIES PRIOR TO THE FAILURE

24th Avenue Connector Adit

In 1994, tunneling started for the Richmond Transport, a 14-foot diameter concrete pipe constructed below the main access street in the area, El Camino del Mar ([Figure 1](#)). The Richmond Transport temporarily stores combined sewage and storm water. At the time of the failure, the Transport was under construction and extended between the East Portal in Lobos Creek, (approximately 200 feet east of the incident area, [Figure 1](#)) and the West Portal, approximately 10,000 feet west. The Transport had been excavated and lined and was near completion. Near the incident area, the top of the Transport is between 40 and 60 feet beneath El Camino del Mar.

In 1994, an 80-foot long adit (or, tunnel with one end) was mined starting from the Richmond Transport toward the brick sewer. The adit was to have accommodated the future connector pipe between the brick sewer and the Richmond Transport ([Figures 1, 4 and 5](#)). The loose dune sand soil was pre-grouted using chemical grout pumped from the Richmond Transport tunnel using borings advanced along and around the adit alignment. After grouting, the adit was hand-mined upwards at a 33 percent grade with a horseshoe-shaped cross section about 10 feet wide. The ground was supported by spiling (steel rods pushed ahead of the face at roof level) and steel set ribs on four-foot centers. During mining approximately 34 cubic yards of sand from the roof and sides collapsed into the adit. The loose sand ground around the fallen sections were treated with additional chemical grouting in an attempt to mitigate further collapses. No settlement monitoring of the sewer or ground surface above the adit was performed except at the street and sidewalk.

During mining in August 1994, two small sinkholes were observed on the ground surface near the end of the adit. The small depressions eventually coalesced between August 1994 and late 1995 to form one depression (sinkhole) about 10 feet in diameter and 7 feet deep, centered about 8 feet from the end of the adit ([Figure 4](#) and [Figure 5](#)). The sinkhole was located adjacent to the brick sewer ([Figure 4](#)). Relative to the topography as surveyed in February 1995, the distance between the sewer and the bottom of the sinkhole was about 2 feet ([Figure 5](#)). The top of the adit terminated 5.5 feet beneath the brick sewer east of the Billman property driveway.

The brick sewer was inspected in 1989 and 1994. Tree roots several feet long were observed to penetrate the sewer in the section later involved during the incident. Photographs taken during the inspections showed sand clinging to the root masses, indicating infiltration had occurred through the brickwork. A crack was observed on the east side of the sewer in 1994, with an associated stain on the brickwork apparently caused by flowing water. The sewer was surveyed in May 1995, but the condition was not documented.

Overflow Structure

Improvements to the Sea Cliff area sewage collection and distribution system were implemented at the same time as construction related to the nearby Richmond Transport. In order to modernize the nearby Pump Station, sewage was temporarily stored in the brick sewer to allow work to proceed in relatively dry conditions without spilling sewage to the ocean. In 1995, the concrete Overflow Structure ([Figures 1, 6 and 7](#)) was installed beneath Sea Cliff Avenue on the alignment of the 24th Avenue brick sewer 1400 feet downstream of the incident site. The structure is a cubic chamber about 10-foot square in plan and 10 feet high, containing a 14-inch high weir at the bottom of the sewer to divert dry-weather sewage to the nearby pump station ([Figures 6 and 7](#)). During construction, a 12-inch high temporary concrete berm was built on the weir to increase dry-weather storage capacity. However, storm flows passed over the berm to discharge into the ocean ([Figure 6](#)). The diversion weir and berm reduced the vertical diameter of the brick sewer from 72 to 46 inches.

During re-construction of the Pump Station and improvement to the local sewage infrastructure, a temporary metal “Contractor’s gate” was installed at the downstream portal of the Overflow Structure ([Figures 6 and 7](#)). The gate was raised and lowered via a cable attached to a restraint located in an access hand hole at the street surface. Fully raised, the bottom of the gate hung six inches below the top of the brick sewer. The intent of the temporary gate was that it be used only when work was performed in the Pump Station, which would require cutting off dry-weather flow from the Overflow Structure to the Pump Station. The gate would then be fully lowered to act as a temporary dam so that the 6-foot sewer would store sewage for the required period. If not lowered, raw sewage would have flowed to the ocean outfall, thus incurring fines from regulatory agencies.

Billman Driveway

Several days before the failure, the Billman driveway ([Figure 4](#)) was paved with thousands of distinctively shaped gray paving blocks. Also, a new gatepost had been constructed that weighed about 18 tons. Additionally, a new concrete planter was built at the toe of an old, high brick masonry retaining wall between the Yee and Billman properties ([Figure 4](#)).

DESCRIPTION OF EVENTS DURING THE FAILURE

Rain started to fall heavily about 0100, December 11, 1995 ([Figure 8](#)). At about 0200, surveyors drove past the incident site and observed nothing unusual. At 0210, the residents of the Billman property, whose home overlooked the incident site, observed a deep pit in the former location of his driveway and a 30-foot long jet of water “shooting” from the sewer exposed in the pit. At 0214, sewer manhole covers above the Overflow Structure on Sea Cliff Avenue blew off their rims, and a 2-foot high column of sewage gushed from the manholes and flowed down Sea Cliff Avenue. At about the same time, sewage began to flow up from the floor drains of three residences on the north side of El Camino del Mar opposite the failure site,

and in one residence, sewage flowed out from a toilet bowl. Sewage also flowed from a manhole on 25th Avenue at about 0230.

Sewage discharge from the Overflow Structure manholes and residential drains stopped about 0245. By this time San Francisco Fire Department staff were on the scene and the documented record improved significantly. At about the same time, parts of El Camino del Mar began to collapse into a large pit, and the sewer was seen to be severed. At about 0305 to 0315, surveyors in the Richmond Transport, approximately 9000 feet west of the incident site, were chased out of the West Portal by a two-foot high wave of water. Shortly after they escaped, the West Portal shaft filled with water. Sometime before dawn, the attached garage of the Yee residence fell into the pit ([Figure 2](#)). The pit caused by the ruptured sewer grew until about 0730, when the historic Billman home fell into the void ([Figure 9](#)). Several families were evacuated from the neighborhood as the pit undermined the sand underlying their homes.

Discharge from the sewer and eroded debris partially filled the Lobos Creek valley adjacent to the failure site until about 0900, when it overtopped the East Portal shaft ([Figure 1](#)) and flowed into the Richmond Transport. Thereafter, sand, sewage and water surged from the West Portal shaft (10,000 feet west of the East Portal Shaft) crossed the Great Highway and Ocean Beach and discharged into the Pacific Ocean. Approximately 9630 cubic yards of sand and debris were later removed from the Richmond Transport.

Discharge from the ruptured sewer was eventually halted by the placement of a plug of approximately 100 cubic yards of concrete in the sewer upstream of the incident site. About 30,000 cubic yards of emergency fill was then placed in the void to stabilize the steep slopes and prevent further property loss.

Soon after the failure, a 6-foot high safe ([Figure 10](#)), a small safe and portions of a vase were found in the Overflow Structure. It was eventually discovered that all these objects originated from the garage of the Yee residence ([Figure 4](#)). There was little other debris in the Overflow Structure, on the beach below the Outfall. Neither was there much debris in the sump of the Pump Station, other than sand, a some pieces of red brick and some fragments of wood.

SCOPE OF THE FORENSIC INVESTIGATION

Evidence of the initiation of the failure was destroyed or buried beneath some 30, 000 cubic yards of emergency fill placed to stabilize the perimeter of the eroded area. Causative events had to be reconstructed from a variety of sources: oral and visual recollections from neighbors and local contractors, physical evidence, air photographs, news accounts and site investigations. To reconstruct the events leading to the failure, the remaining portions of the brick sewer was inspected; furniture (found in the Overflow Structure) was retrieved and analyzed; residents, construction personnel, and City and County of San Francisco employees were interviewed; information related to the design and installation of recently constructed facilities was reviewed; topographic elevations of catch basins, manhole covers, drains, and clean-outs were surveyed; rainfall data and ensuing sewer flow data from a January, 1996 storm were collected and analyzed; the primary sewer system of the Sea Cliff area was numerically modeled; a physical model of the

Overflow Structure was reviewed, and geological, geotechnical, and hydraulic engineering analyses were performed.

FINDINGS OF THE FAILURE INVESTIGATIONS

Rainfall and Storm Water Flow in the Brick Sewer

There were no data for the December 11 storm in the Sea Cliff area, but data from other San Francisco locations indicated that the storm had a recurrence interval of between 2 and 5 years. At San Francisco State University, south of the incident area, 15-minute data indicated heavy rain fell between 0100 and 0300, with the greatest amount (0.37 inches) falling between about 0145 and 0215 ([Figure 8](#)). As such, the event was unusual but not extraordinary and on average, several 2-year to 5-year events had been accommodated by the brick sewer in its 100 year history, with no reported overflows in the Sea Cliff area.

But, as indicated above, there were incidents of flooding from manholes and residential drains during the storm. For instance, storm water discharged from manholes above the Overflow Structure, more than 15 feet above the crown of the sewer. Three residences opposite the Billman home, suffered sewage discharges from floor drains at about 0200. In one case, backflow from the toilet in one of these residences resulted in documented phone calls to the Fire Department and a commercial sewer cleaning company. A city employee witnessed the discharge of sewage from the manholes above the Overflow Structure at 0214, and radioed his observations to his dispatcher at the Oceanside treatment plant. The documented times of the calls were useful in understanding the timeline of events.

The construction of the incident timeline required corroborating facts gleaned from interviews with Sea Cliff residents. In general, memories of incidents that occurred in the middle of the night were consistent. However, confusion resulted from the firm insistence of a police officer that he had observed collapse of El Camino del Mar before about 0200, well before the earliest reports of flooding from local residents. Scrutiny of police car/dispatcher records, and interviews with other police officers, revealed that the officer had actually been enjoying his mid-shift break at an all-night restaurant over a mile away, and did not arrive on the scene for at least an hour after the time that he thought he had arrived at the site.

After the failure, grease and sewage grits were found on the sides of the Overflow Structure manholes, showing that sewage flow from the manholes had occurred. However, no grease was found in Manhole 1 ([Figure 6](#)) a few feet downstream of the Overflow Structure, indicating that no sewage had flowed from that manhole. After the failure, a high water mark of green grass and other recent debris was observed 15 feet above the crown of the sewer in a sealed manhole downstream of the incident site. Other hydraulic observations, or manifestations of flow or non-flow, from manhole covers along the alignment of the sewer

were recorded. Upstream of the incident site, a transition was observed in the sewer between soluble and friable encrustation and non-soluble encrustation, which marked the upstream limit of full-pipe flow. [Figure 11](#) shows the locations of the hydraulic observations.

Manning's Equation was used to fit the hydraulic observations to an envelope of hydraulic grade lines that approximately matched the observed high water and flood events. On the basis of a range of hydraulic grade lines, it was estimated that there had been a maximum hydraulic head of about 16 feet above the crown of the sewer at the failure site near the Billman property ([Figure 11](#)). Computer modeling established that the flow in the sewer ranged from 330 to 415 cubic feet per second (cfs). Analysis showed that elevation of the hydraulic grade lines could match the observed flooding and high-water marks only if the cross-sectional area of the brick sewer was effectively restricted by 55 to 65 percent at the Overflow Structure at the estimated flow range of 330 to 415 cfs. In the absence of such a constriction, the Hydraulic Grade Lines would flow at, or about, the height of the sewer.

Condition of the Sewer

Following the incident, persistent cracks in the crown of the sewer were observed upstream and downstream of the incident area. The City of San Francisco commissioned a detailed inspection and assessment of the sewer in the Sea Cliff area and determined that it was in good condition. In the summer following the incident, the jacketed ("1934") section of the sewer was exhumed and crown cracks were found, but there was little evidence that the sewer had deformed significantly. The concrete jacket was up to 2 feet thick, and also in very good condition. The non-jacketed portions of the sewer were completely crushed and no indications of the sewer's pre-failure condition were discernable.

Cause of Over-Pressurization of the Sewer

Initially, the contributions of individual components inside the Overflow Structure to the constriction of the sewer flow and the elevation of the hydraulic head were not determined. At the time of the release of the public report (Failure Analysis, 1996; Medley and Delp, 1998), it was known that the Overflow Structure, or some component(s) of the structure, was in some way responsible for constricting the flow of the storm, but it was not known which particular element was the cause. However, following detailed analysis, a review of City video tapes of the sewer inspections a few months before the failure, and observation of a physical model of the Overflow Structure built by the city consultant who designed the Overflow Structure, it became very clear that the cause of over-pressurization was related to the temporary Contractor's gate ([Figures 6](#) and [7](#)), which apparently had been left lowered in a partly closed position at the time of the incident.

Role of the Sinkhole

The sinkhole developed, between August 1994 and the time of the incident, into a pit that extended to within 2 feet of the sewer. Detailed geotechnical and hydraulic analyses showed that pressurized water leaking from a cracked sewer for a sustained period of time would preferentially and quickly flow toward a

free surface at the base of a sinkhole only two feet away, rather than through several more feet of intact soil. Flow toward a nearby free surface was also preferred to drainage toward a relatively deeply buried void such as the adit, which was substantially enveloped in chemically grouted sand. Accordingly, it was considered certain that the failure initiated adjacent to the sinkhole rather than anywhere else in the area.

RECONSTRUCTION OF INITIATION AND PROGRESSION OF THE FAILURE

Heavy rain started between 0130 and 0200 and the sewer began to back up at the Overflow Structure. Sometime before 0210, below the Billman property, the increasing pressure caused the water to leak from cracks in the top of the brick sewer adjacent to the sinkhole because the approximately 2 feet of soil cover was less at the sinkhole location than elsewhere along the sewer alignment (Cross Section AA', [Figure 12](#): see [Figure 4](#) for location of the section). The water pressure and short flow path to the sinkhole caused the sand to pipe (scour due to water pressure). The lessened soil constraint led to relaxation of the brick sewer, resulting in widening cracks.

As the water pressure rose, the force and volume of water jetting from the cracks increased, thus scouring more sand, quickly leading to additional relaxation of the soil pressure confining the sewer. The scouring due to the pressurized water jet progressed downstream along the sewer. Soil from around the sewer, vegetation, trees and the gray paving blocks of the new driveway flowed down slope into Lobos Creek. By 0210, when the owner of the Billman property first saw the exposed sewer, erosion and uncovering of the sewer had advanced as far northward as the area of the planter and brick retaining wall between the Billman and Yee properties ([Figure 13](#)). Removal of sand at the foundation of the planter led to undermining of the planter. The adjacent brick retaining wall then collapsed, and exposed the east side of the Yee property garage and northeast corner of his house to undermining. The garage slab tilted and the 6-foot heavy safe rolled across the slab and fell into the pit, later joined by the smaller safe and vase.

At about 0240 to 0245, after some 40 minutes of sustained pressurized leakage, scouring and erosion, the sewer eventually broke. The final rupture may have been caused by decreased soil support from undermining; puncture of the sewer by falling debris (such as the falling safe or the toppled brick retaining wall); or eventual bursting of the sewer by the sustained high water pressure. Regardless of the cause, the rupture immediately depressurized the sewer, which caused an abrupt cessation of flow from the manholes at the Overflow Structure (and at residential drains on the north side of El Camino del Mar) at about 0240 to 0245. Debris, including the safes, entered the ruptured downstream end of the sewer. However the ruptured end of the sewer was not long open as few large items were found in the brick sewer or on the beach around the outfall.

Once the sewer ruptured, the full force of the storm water was unleashed upon the sand soil supporting the sewer. Aggressive erosion resulted in northerly and downward scour toward Lobos Creek and the 24th Avenue Connector adit ([Figure 13](#)). As the water flowed north and downward toward the creek, erosion of the bottom of the south-facing slope of El Camino del Mar occurred, and a rapid series of small slope failures resulted. At about 0245 to 0250, water eventually breached the thin temporary ground support inside the 24th Avenue Connector adit. Once the water had entered the adit, it flowed unimpeded down the Richmond Transport, to reach the surveyors, about 9000 feet away, some 15 to 20 minutes later.

A few gray brick paving stones from the Billman driveway were later found in the Richmond Transport, suggesting that the driveway had been largely washed into Lobos Creek by the time the adit was breached. The ruptured sewer collapsed southward as it undermined itself and the resulting erosion continued unabated until 0736 when the Billman house fell into the void. Sand and up to 25 feet of water and debris resulting from the erosion was deposited in the valley of Lobos Creek and over-topped the shaft of the Richmond Transport tunnel about 0900. The Richmond Transport tunnel then became a drain as sand, sewage and water surged from the West Portal shaft over the Great Highway and into the Pacific at Ocean Beach. Erosion was halted on December 12, 1995 by plugging the sewer with 95 cubic yards of concrete upstream of the incident break.

CONCLUSIONS

The factors that contributed to the failure included (1) the partial lowering of the temporary Contractor's gate in the recently constructed Overflow Structure downstream of the failure site that constricted storm water flow, and (2) reduction of ground support around the pipe due to a sinkhole that had formed above the adit, and adjacent the sewer.

The top of the 24th Avenue Connector adit was approximately 5.5 feet below the bottom of the brick sewer at the site of the future transition. Mining of the adit, and the development of the approximately 7-foot deep sinkhole above the adit, led to relaxation of the soil support around the sewer. In addition, other cracks may have been present in the sewer, as one was noted during a 1994 inspection, and longitudinal cracks were observed in the crown downstream and upstream of the incident site. In the vicinity of the sinkhole, tree roots penetrated the sewer indicating that additional routes for exfiltration existed through the brickwork.

However, neither the deformation, cracking or other defects was sufficient to cause failure during high flows in the winter of 1994 to 1995. It required constriction of storm water flow due to the partly lowered Contractor's gate in the recently constructed Overflow Structure to pressurize the brick sewer. The hydraulic grade line in the failure area was approximately 16 feet above the crown of the sewer. Without the Overflow Structure, the sewer would have generally flowed full, but the hydraulic grade lines would have been at about the same elevation as the top of the sewer in the area of failure.

Without the sinkhole, but if the pressurization had still occurred, it was probable that that the catastrophic failure of the sewer may not have occurred, since progression of the pit as far as the Yee garage would likely have had to start several tens of feet upstream from the sinkhole location (where the soil cover was shallowest at about 5 feet). Consequently, the progression of the eroded pit toward the Yee garage, Billman gatepost and Billman/Yee retaining wall would have taken longer.

ACKNOWLEDGEMENTS

The successful forensic investigation on which this paper is based is due to the hard work of many Exponent staff, the City of San Francisco and the City's contractors. Particular thanks are extended to Louise

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AUTHOR PROFILE

Dr. Edmund Medley, PE, CEG, is a geological engineer with international experience in geological and geotechnical engineering. His 30 year career includes chapters as a mineral exploration prospector, teacher, university lecturer, vagabond and researcher of problems related to the engineering characterization of bimrocks (complexly-mixed rocks and soils). He is currently a Principal Engineer in the Geo³ Group (Geological, Geotechnical and Geoenvironmental Engineering) at Exponent Failure Analysis Associates in Menlo Park, California, where he performs geo-forensic investigations. Dr. Medley is a Certified Engineering Geologist in California and Registered as a Civil Engineer in California and Hawaii. He also holds professional geologist and professional engineer registrations in British Columbia and the United Kingdom.

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Figure 2 – Aftermath of the Sea Cliff Incident: a 200 foot diameter and 40 foot deep pit containing the debris from the collapsed Billman residence. Yee residence in background.



Figure 3 – Remnant of 6-foot diameter brick sewer at the southern limit of erosion. Sewer is confined by loose to medium dense dune sand.



Figure 4 – Location of the initiation of sewer failure. Section AA' is shown in Figure 12.

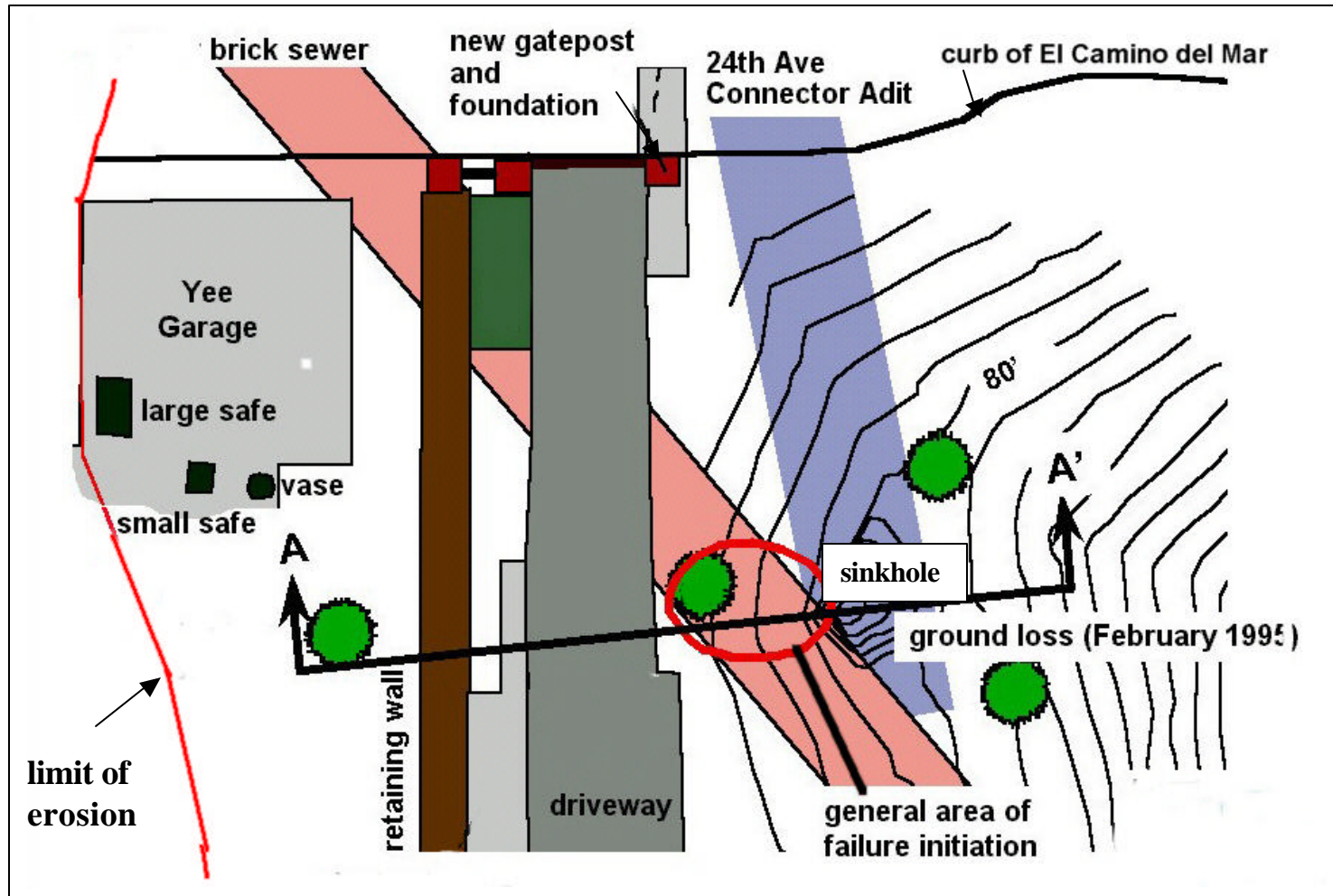


Figure 5 – Profile along Brick Sewer in area of failure. Distance between top of adit (at end) and sewer is 5.5 ft. Distance between bottom of sinkhole and top of sewer is about 2 ft.

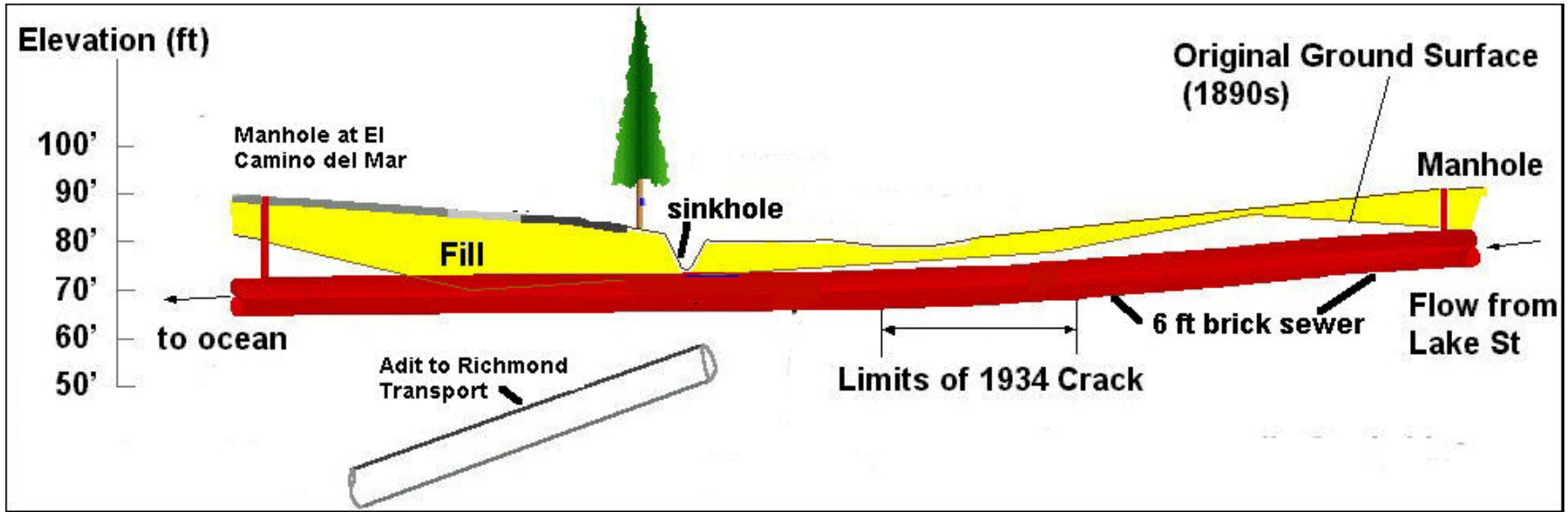


Figure 6 – Profile Through Overflow Structure.

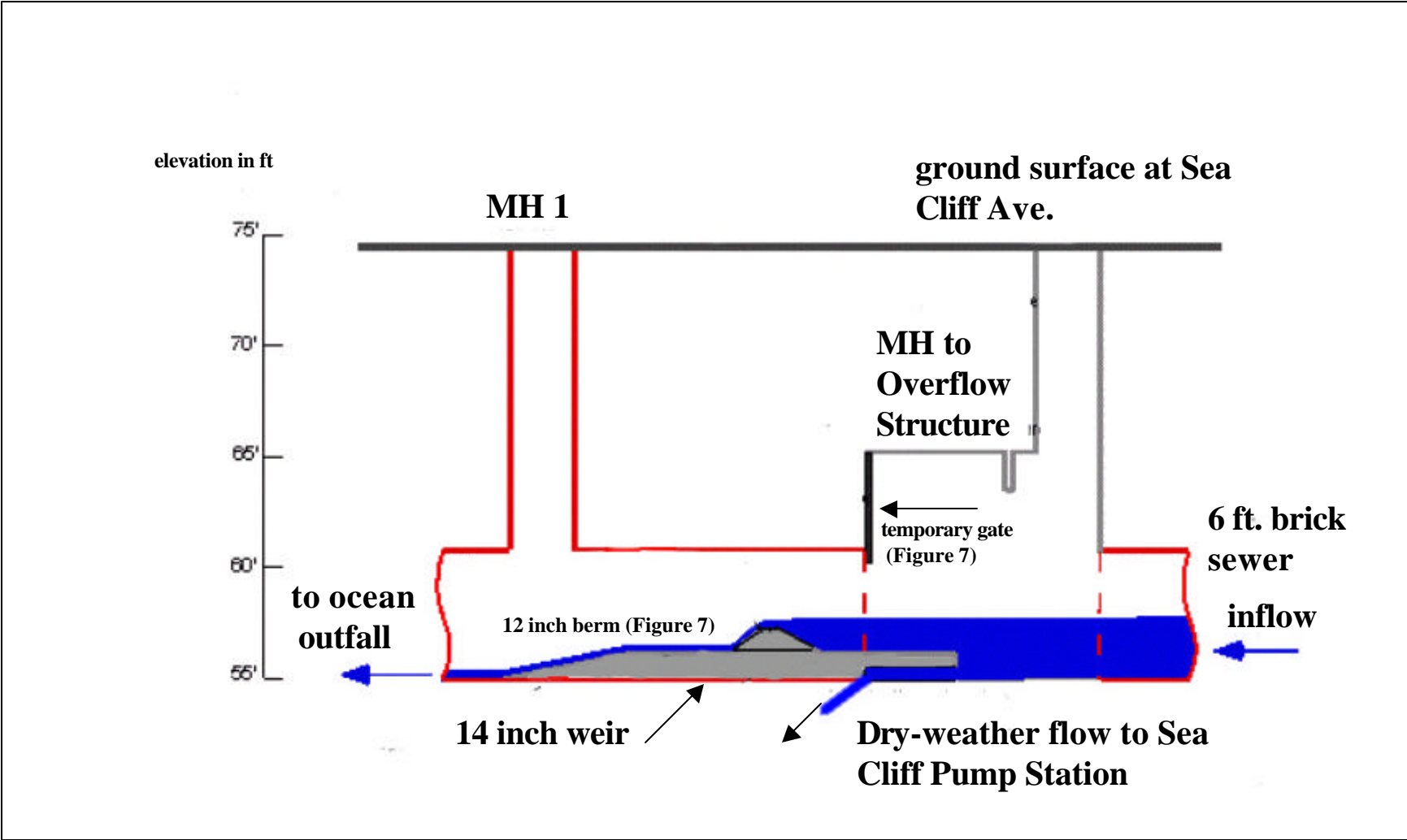


Figure 7 – Overflow Structure, Looking Downstream.



Figure 8 – Rainfall Data from San Francisco State University for early morning of Sunday December 11, 1995

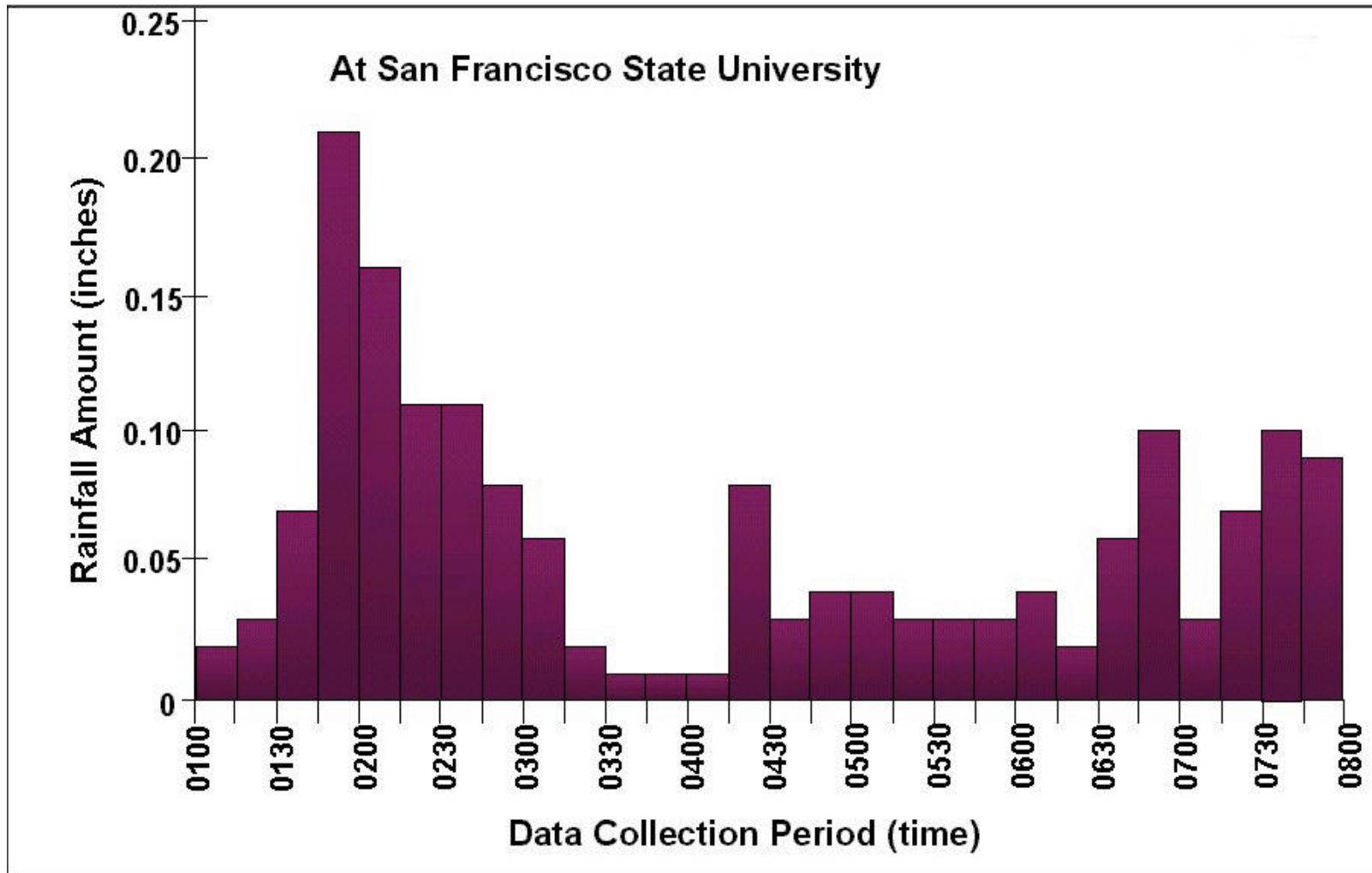


Figure 9 – Collapse of the Billman Residence
(from KTVU Channel 2, San Francisco)



Figure 10 – Large Safe from Yee Residence Found in Overflow Structure



Figure 11– Profile of 6-ft Brick Sewer Showing Hydraulic Grade Line (HGL) and Locations of Hydraulic Observations.

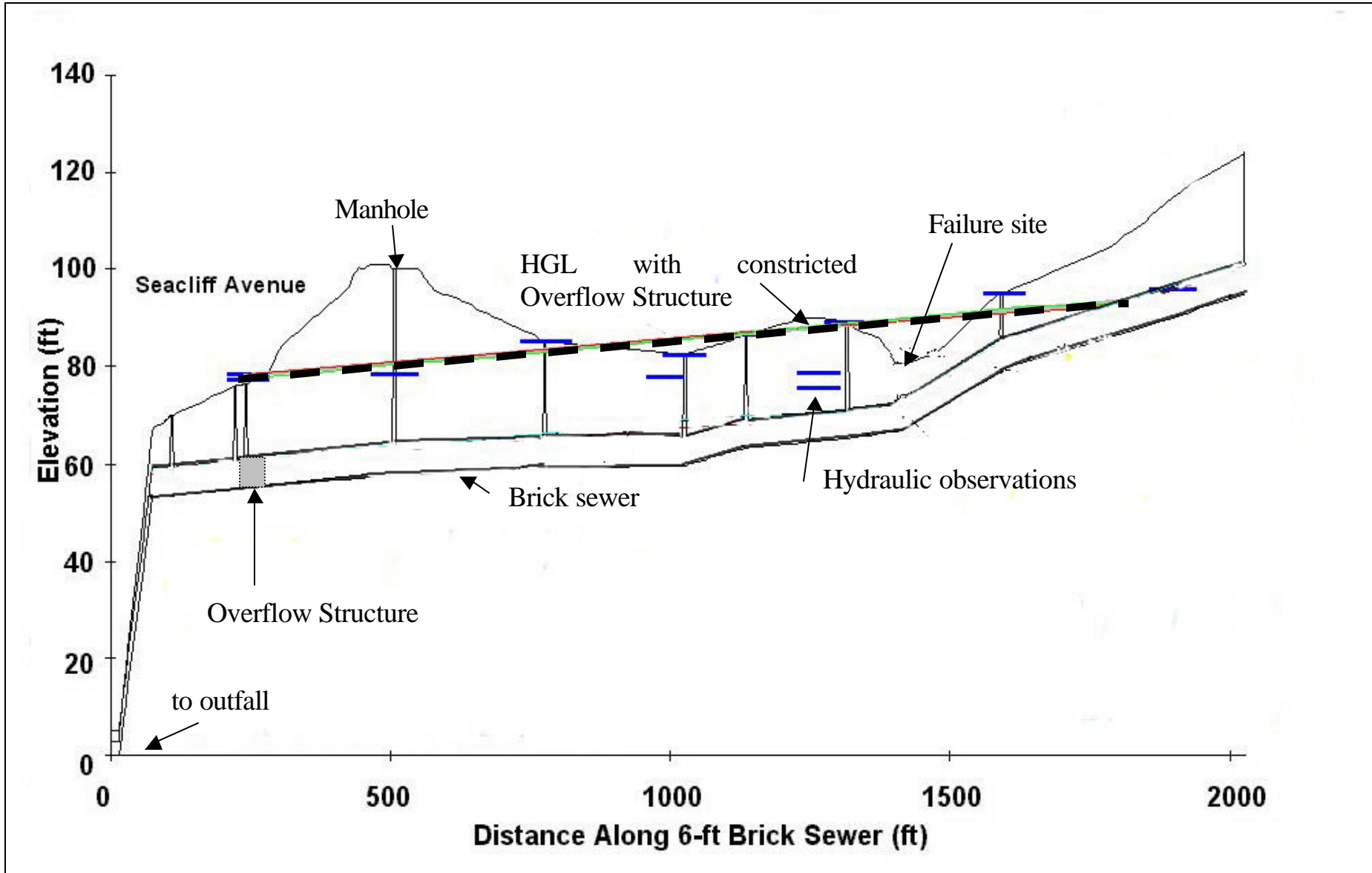


Figure 12- Section AA' (see Figure 4 for location), Showing Initiation of Failure Adjacent to Sinkhole.

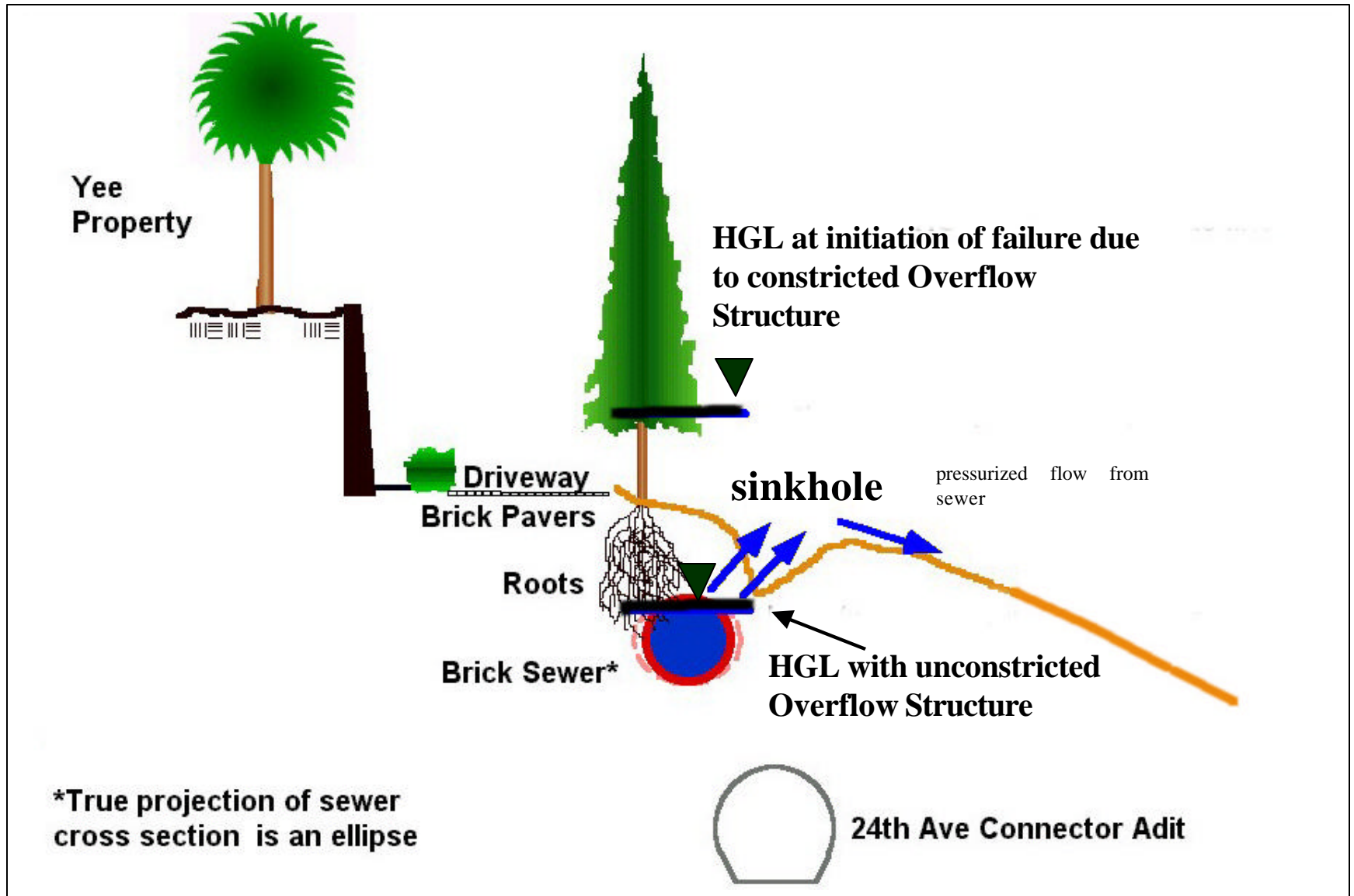


Figure 13 Cross-Section adjacent Yee Residence showing most likely scenario of sewer collapse. Events are: 1: original ground; 2: ground starts to erode; 3: brick retaining wall is undermined and starts to tilt toward driveway; 4: garage slab moves downward as retaining wall moves; 5: heavy 6-foot high safe rolls down tilted slab and falls into pit; 6: safes; gateposts and other heavy object fall onto sewer; 7: sewer breaks; 8: full force of storm water flow is unleashed from broken sewer and rapidly scours downward through sand toward Lobos Creek; 9: discharge from sewer breaches adit and drains to Richmond Transport.

