# Why Did It Fail?

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## The University of Texas at Austin

# Why do structures fail?

- Many reasons:
  - Design (45 to 55%)
  - Construction (20 to 30%
  - Materials (15 to 20%)
  - Administrative (10%)
  - Maintenance (5 to 10%)

# Specific Causes

1. Ignorance/incompetence/inexperience
2. Blunders, errors, and omissions
3. Lack of supervision within organization
4. Lack of communication or continuity
5. Lack of coordination
6. Overemphasis on the bottom line
   (saving money)
7. Administrative deficiencies
8. Maintenance

# Role of Forensic Engineer

- Determine the cause of failure
- Persuasively communicate his findings to the client and/or appropriate judicial venue
- And in some cases, recommend corrections or repairs

# We should learn from failures

- History is one of our greatest teachers
- Some our greatest lessons have come from failures
- Unfortunately, the cause of many failures are sealed by agreement of the involved party and the public never learns some very important lessons
- University of Maryland experience

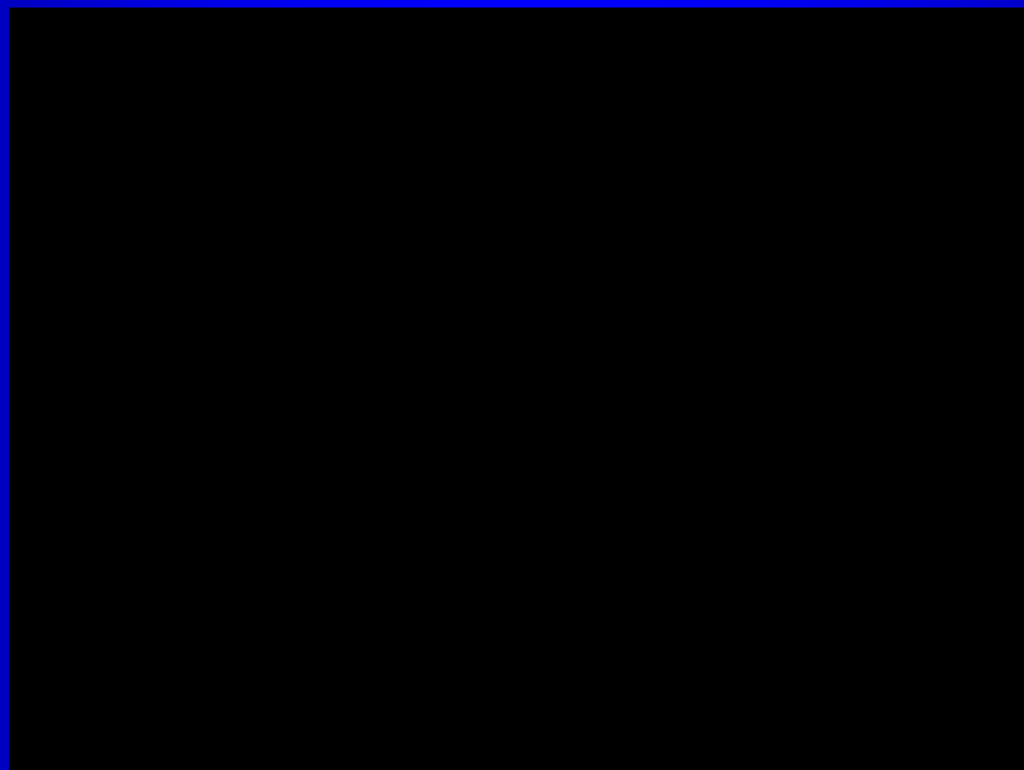
# Let’s look at some failures…

- Tacoma Narrows Bridge Failure: Fowler
- Big Dig Ceiling Panel Failure: Fowler
- Case Study of Foundation Failure: Chancey

# Tacoma Narrows Bridge

- The most famous bridge failure in the U.S.
- It was originally opened to traffic July 1, 1940.
- It collapsed four months later, November 7, 1940, at 11:00 am.
- It had been exhibiting signs of aerolastic flutter since it opened.

# Let's look at what happened…



- The bridge was built with shallow plate girders instead of deep stiffening trusses used on railroad bridges.
- The solid plate girders have a larger surface area to "catch" the wind.
- Open trusses have a smaller area through which wind can pass through.
- The bridge, under 42 mph winds, experienced rolling undulations resulting ina 0.2 Hz torsional vibration mode with amplitudes of up to 28 ft.

- The bridge was effectively divided into two halves.
- The two halves vibrated out of phase with each other—one half rotated clockwise and the other counterclockwise.
- The two halves then alternated direction of rotation.
- The bridge collapsed during this torsional mode.
- A 600-ft.length of the center span broke loose from the suspenders and fell 190 ft. into the water.

# Failure Theories

Fundamental weakness of the Tacoma Narrows Bridge was its extreme flexibility, both vertically and torsionally.

# Replacement Bridge (1950)

- Truss girders allow wind to pass through
- Torsional rigidity was increased
- Wind tunnel testing was performed to verify design

# Most failures are not this dramatic

- Some are due to corrosion
- Some are due to freezing and thawing
- Many are due to improper detailing
- Some due to inadequate codes or not following the codes that are adequate
- Fire causes failure

# The Big Dig
# Ceiling Panel Failure:
## Lessons in Engineering and Ethics


# Central Artery/Tunnel Project

# What is the Big Dig?

- An I-90 highway project – 161 lane miles in 7.5-mile corridor – in central Boston
- Five miles of tunnels, six highway interchanges, 200 bridges
- Increased the highway from 6 elevated lanes to 8 to 10 lanes on the new highway system
- Construction started 1991
- Construction completed December 2007

# What is the Big Dig?

- Original project estimate - $2.8 billion
- Final cost - $14.8 billion
- Dirt removed – 16 million cubic yards
- No. of workers at peak – 5,000
- No. of historic artifacts excavated – 200,000
- No. of cars using old elevated hwy – 75,000/day
- No. of cars projected in 2010 – 245,000/day
- Old travel time – 19.5 minutes
- New travel time – 2.8 minutes

# Timeline

- 1982 – Original estimate pegged at $2.8 billion
- 1991 - Construction begins
- 1998 - Cost estimate jumps to $10.8 billion
- 2003 – I-90 connector tunnel opens
- 2005 – 169 defective panels in I-93
- 2006 – July 10 ceiling panel failures!!!
- 2007 – December, project complete

# Problems

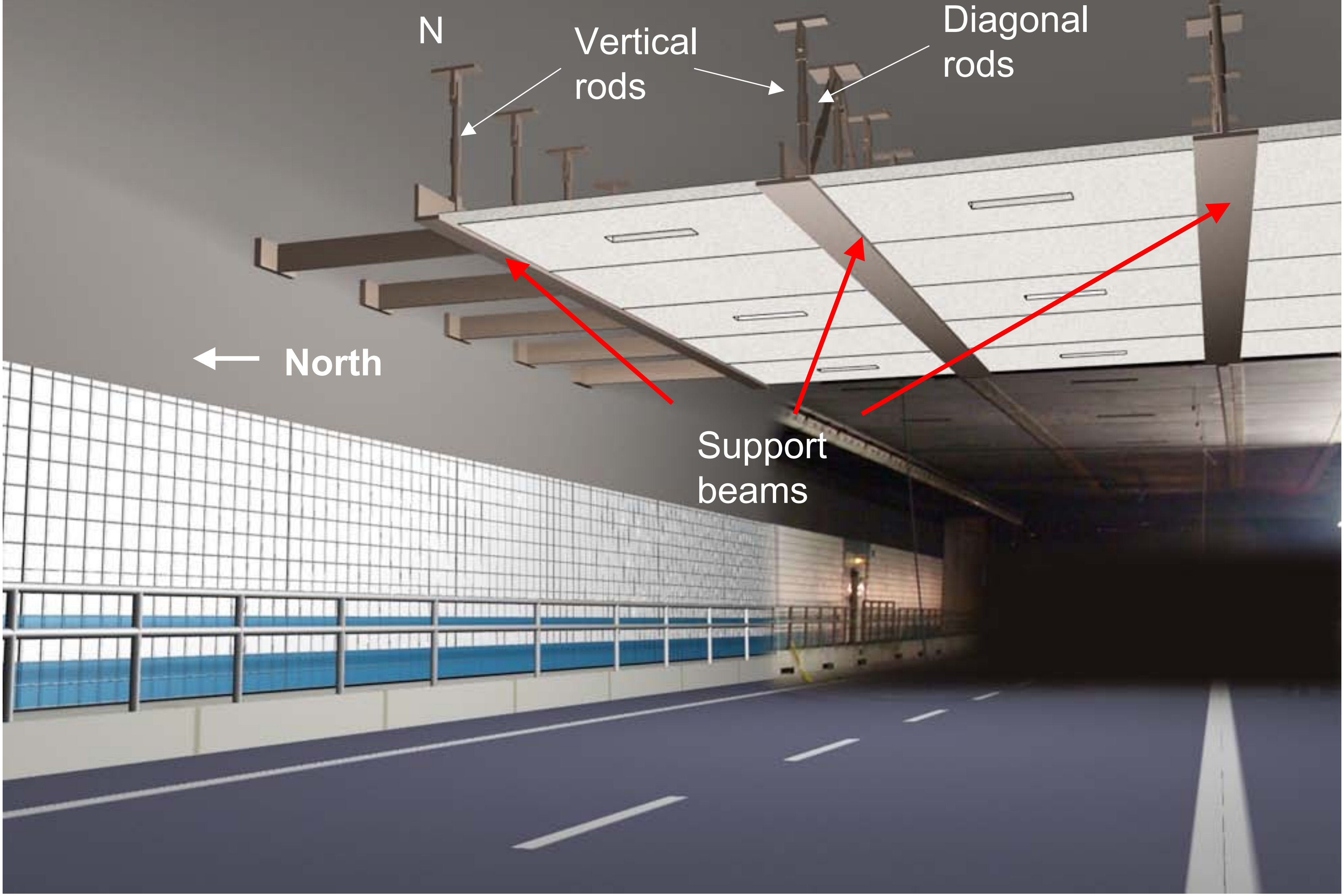
- Financial overrun – $12.0 billion
- Substandard concrete – resulted in indictments
- Leaks – 2,000 to 3,000 were plugged
- Adhesive anchor failures – resulted in a fatality and indictments

# What Happened?

- 7/10/06, 11pm – A 1991 Buick occupied by a 46-year-old man and his 38-year-old wife was traveling east when a section of the tunnel's suspended roof collapsed.
- About 26 tons of concrete and structural framing members fell on the passenger side of car – killing the woman instantly.
- The driver escaped with minor injuries.

# Accident Scene

# Collapse Sequence



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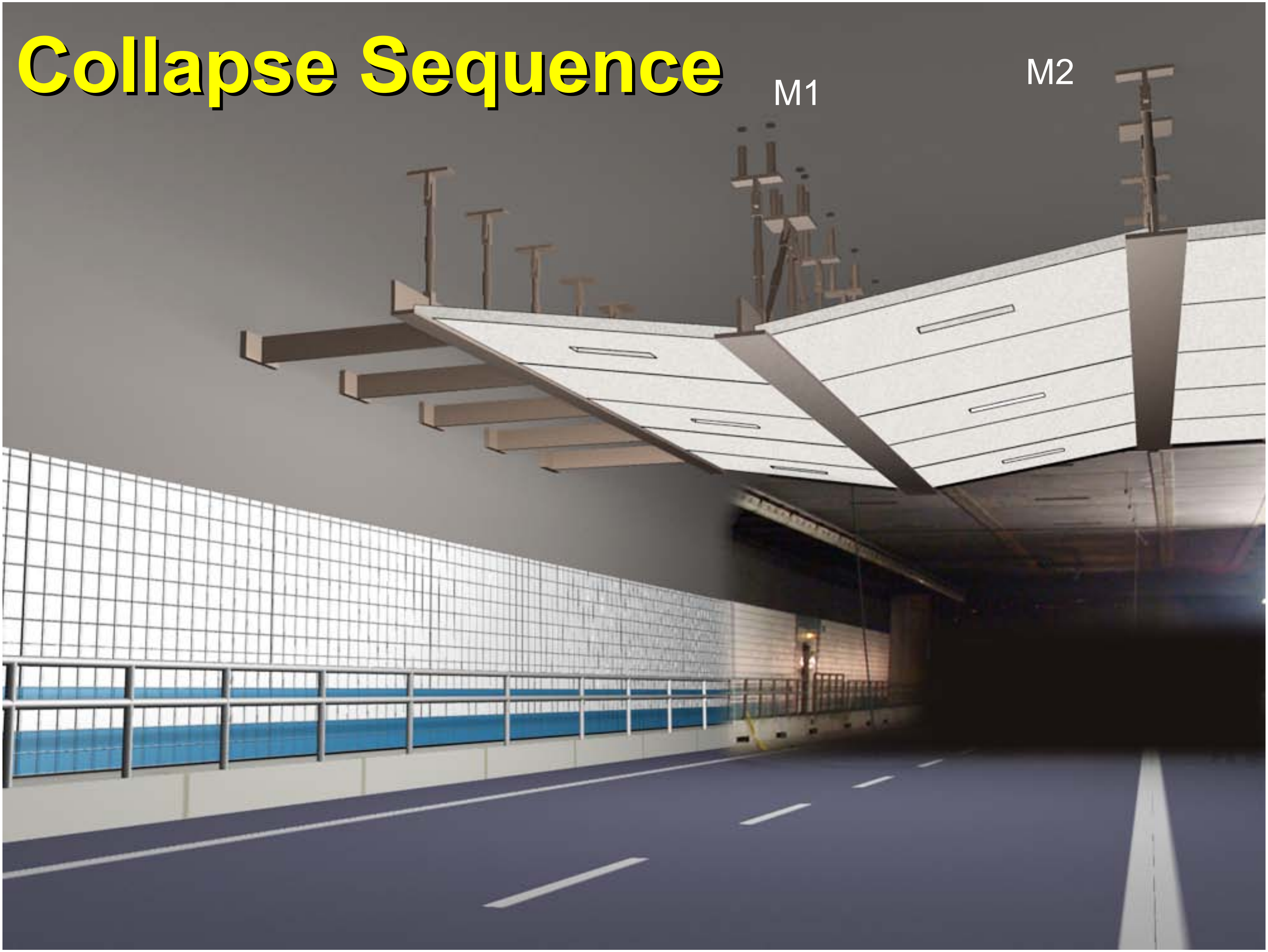

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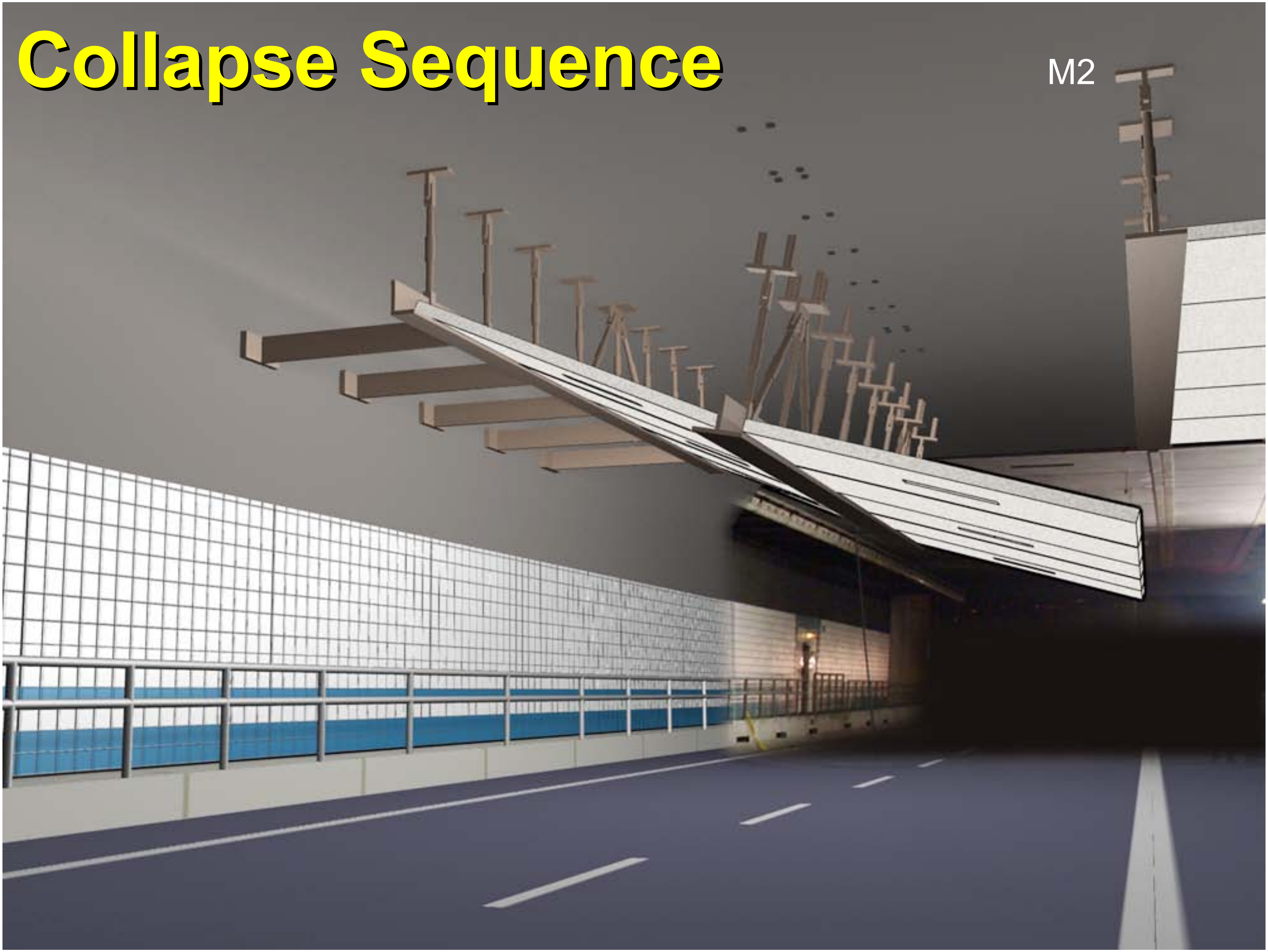

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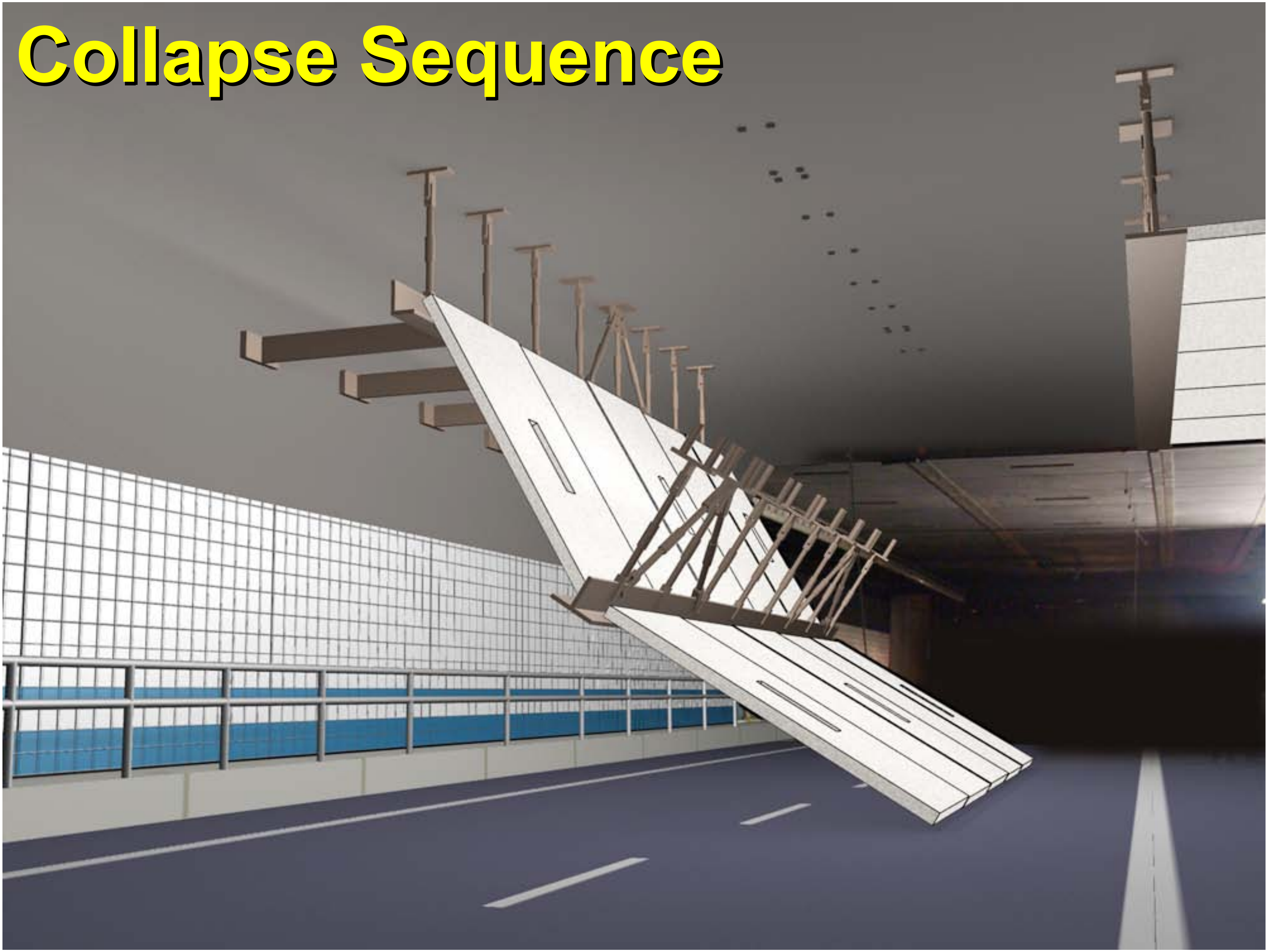

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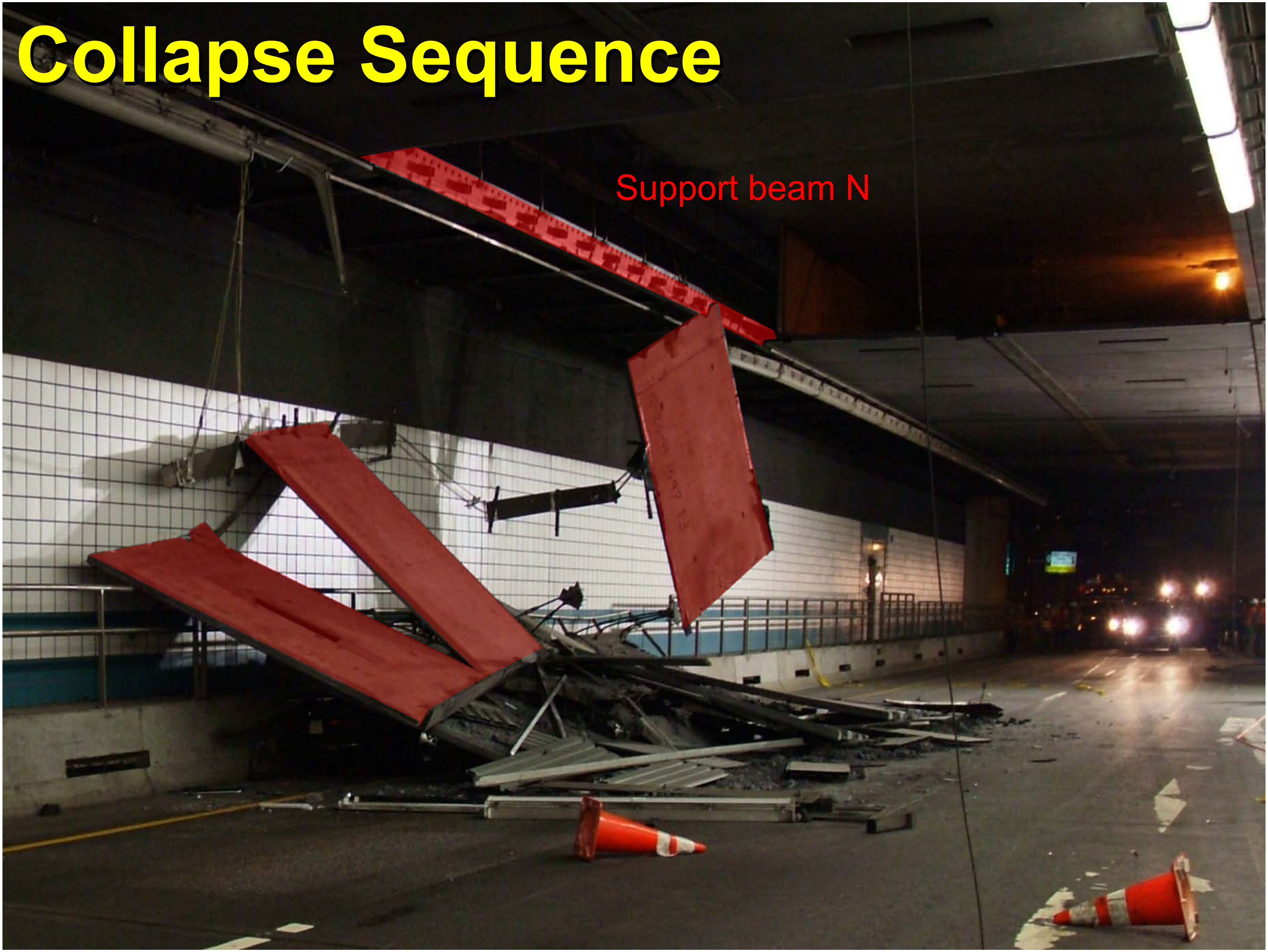


# Displaced Anchors Found in Westbound Tunnel: Accident Waiting to Happen

# Car Crushed by Ceiling Panel

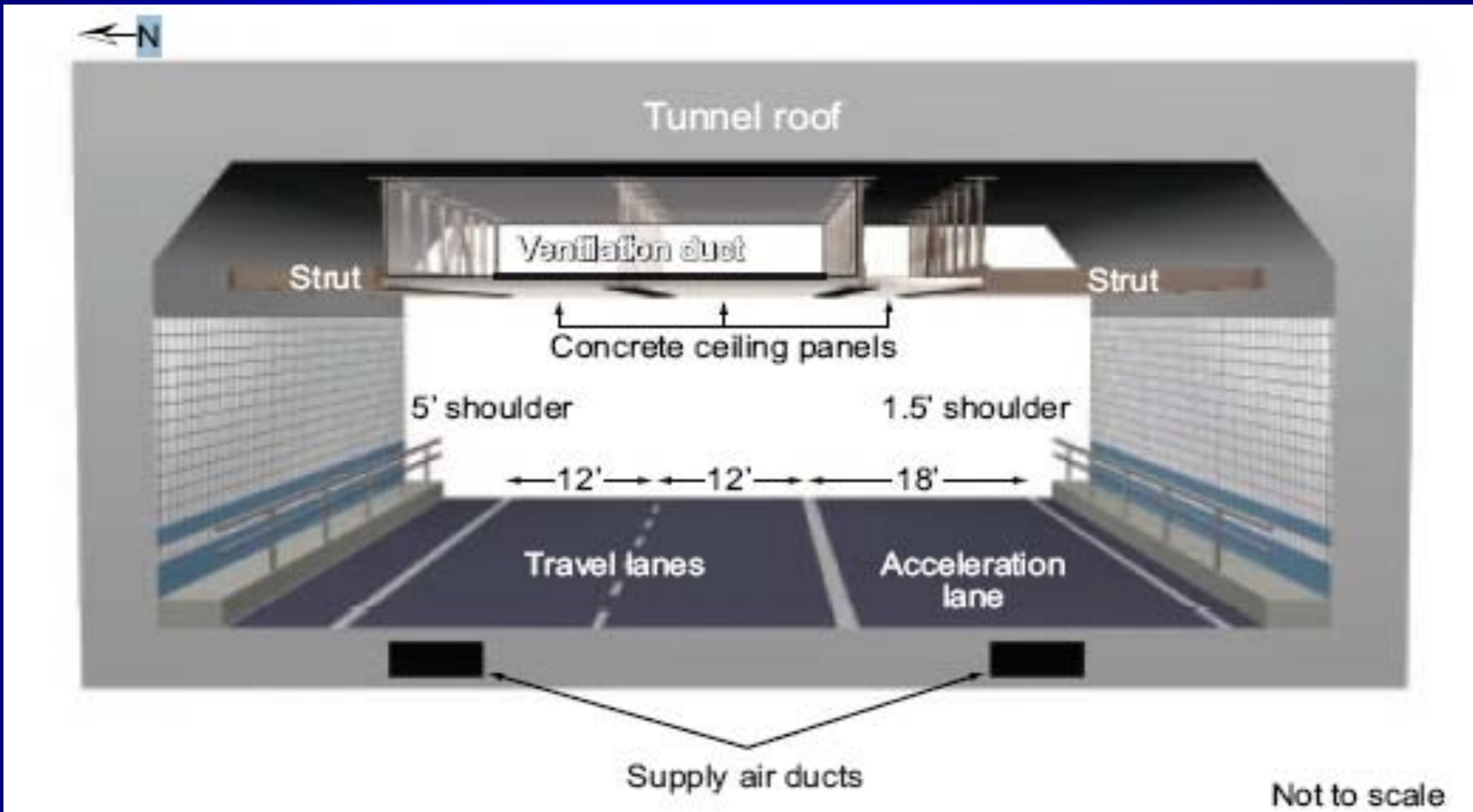
The car that was crushed by falling ceiling panels,
killing passenger Milena Del Valle in a Big Dig Tunnel in Boston.

# Outcome

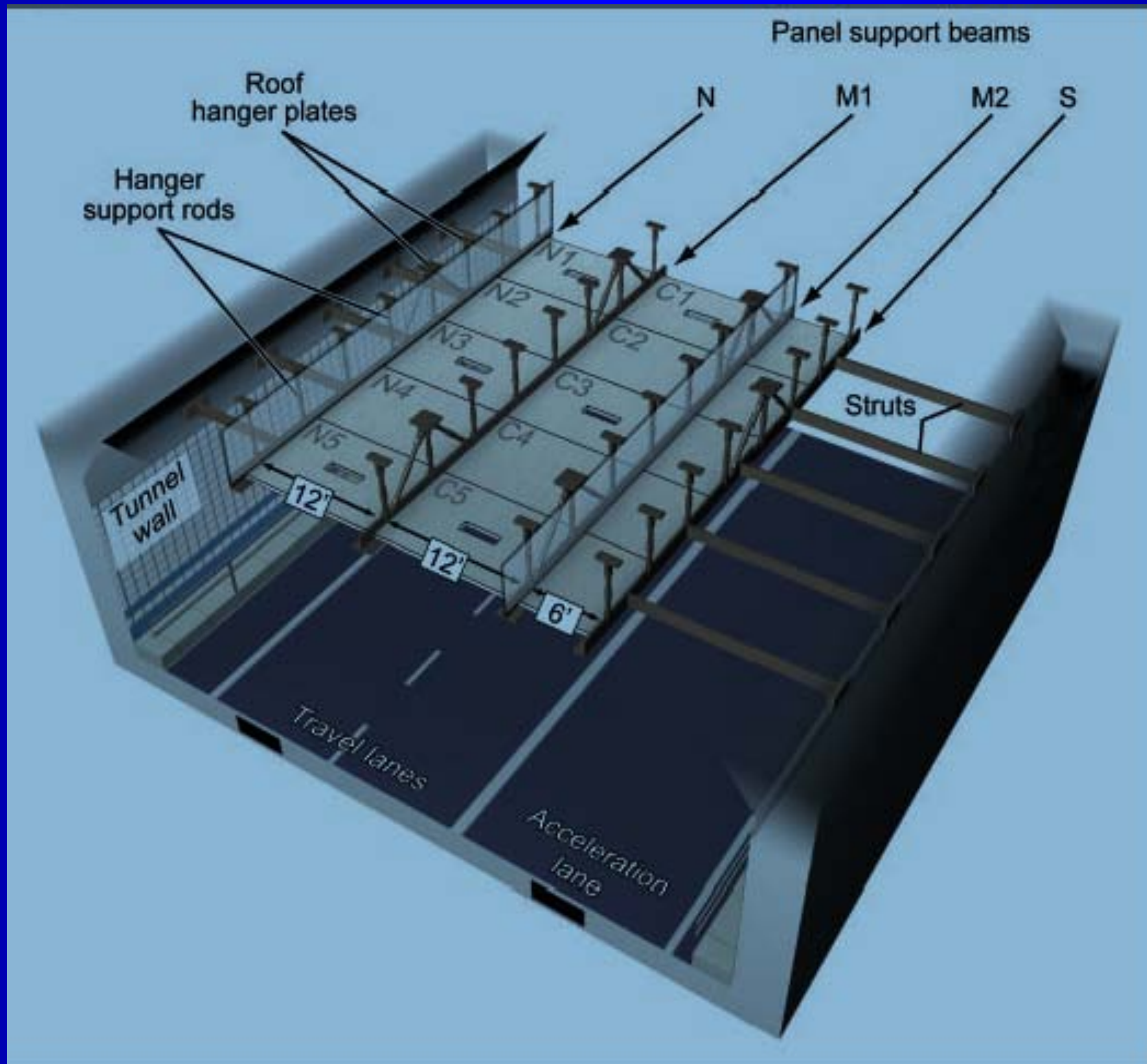
- Ultimately the family of Mrs. Del Valle received a settlement of $28 million from the contractor, Bechtel (project manager), Mass Turnpike Authority, and others
- But this did not end the investigation or litigation - Bechtel and several smaller companies agreed to a $450 million settlement to avoid criminal charges.
- The fastener company and contractor faced criminal charges.

# Let's look at the design…

# The Tunnel Design



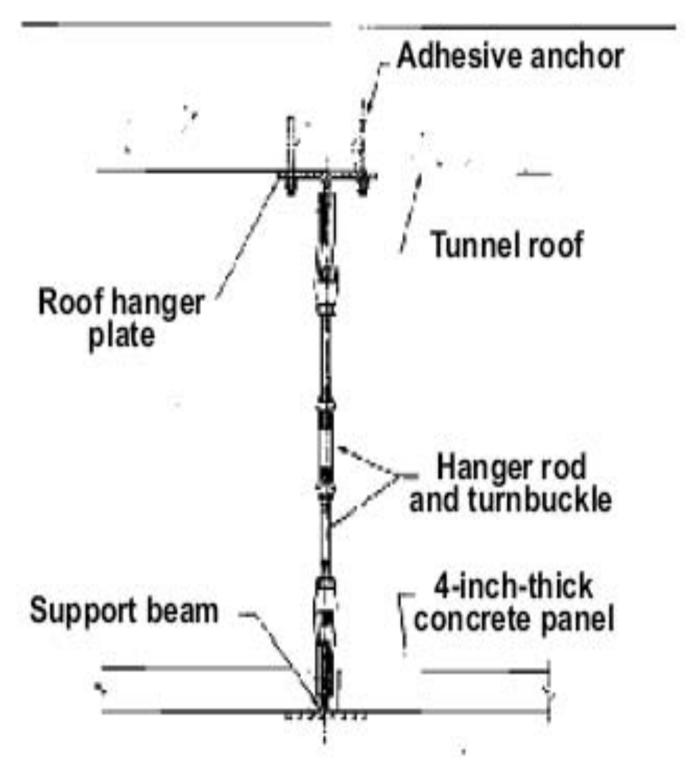
# The Tunnel Design

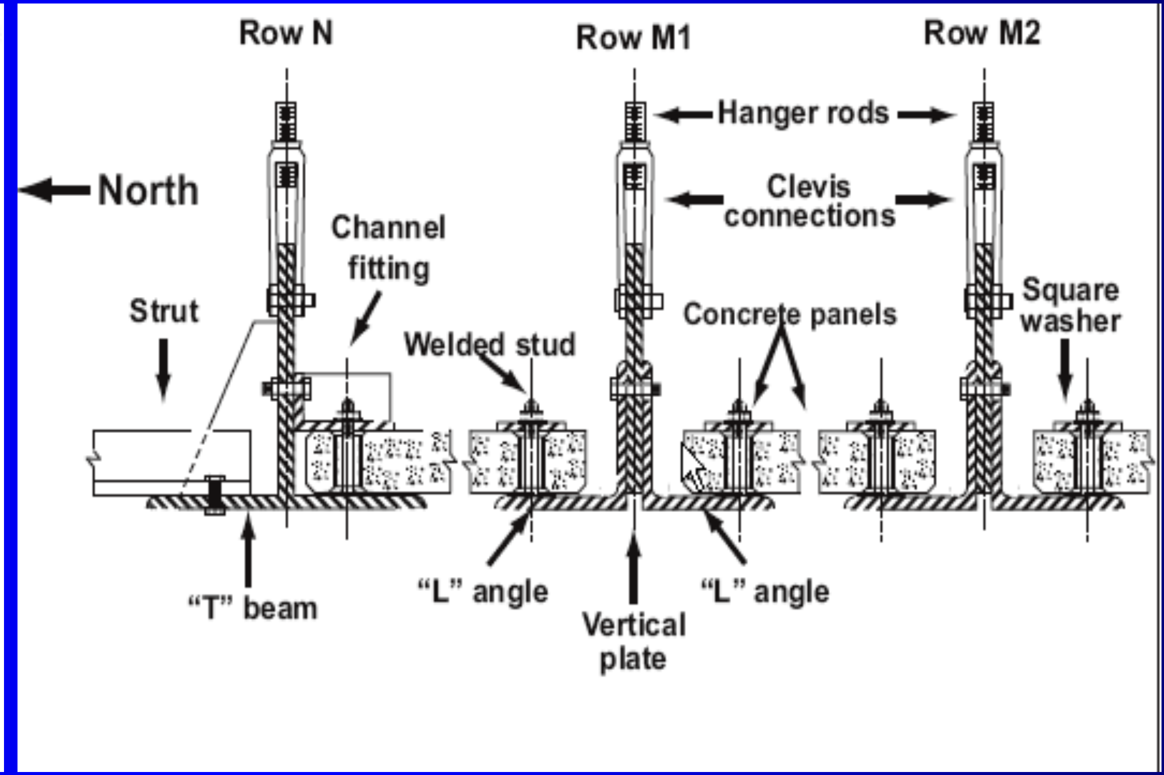


# Concrete Panels

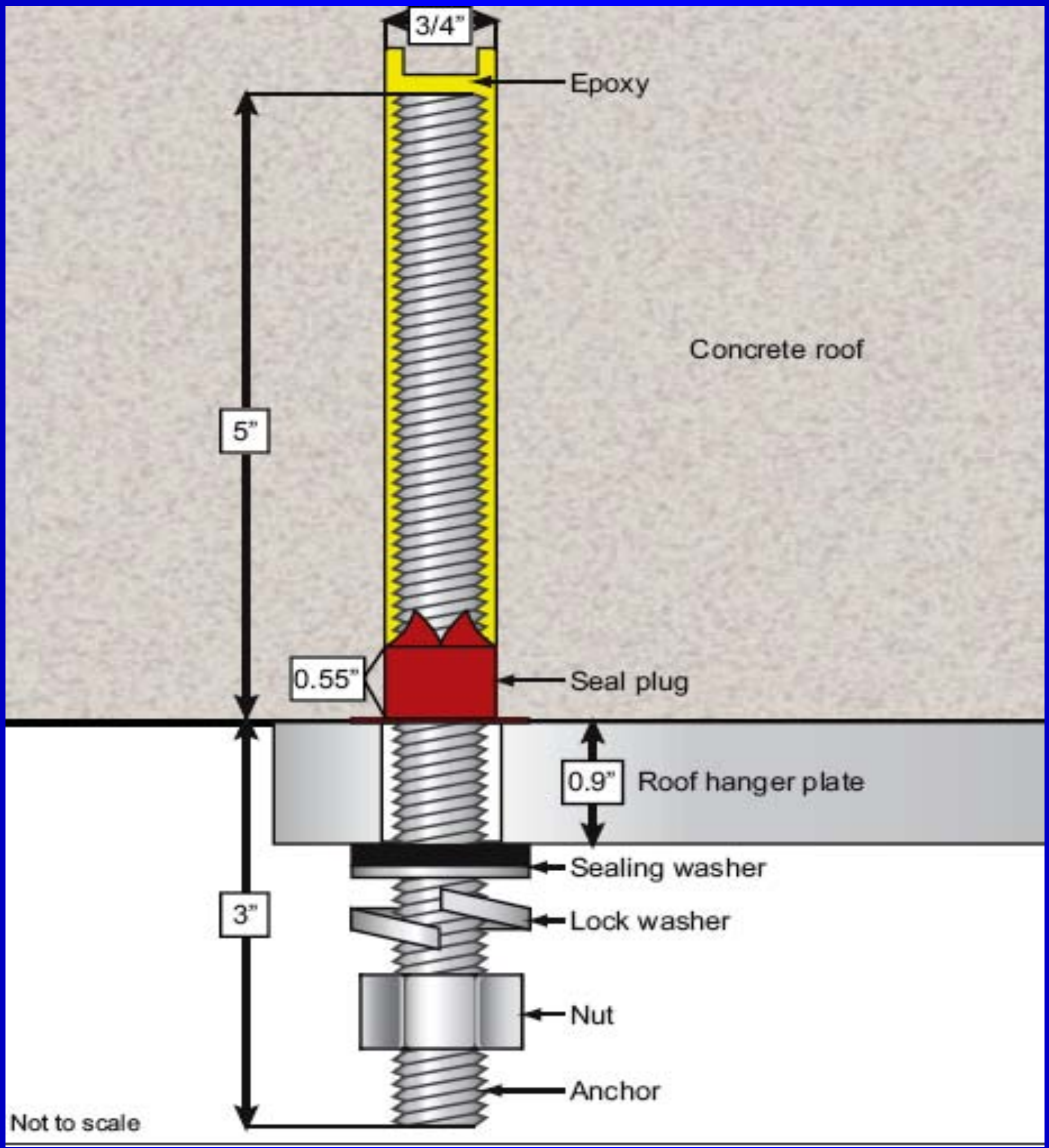
- Three rows of concrete panels all 4 in. thick
  - Two rows 12 ft. wide and 8 ft. long in direction of traffic, each panel weighing ~4,700 lbs.
  - One row 6 ft. wide and 8 ft. long, each panel weighing ~2,500 lbs.
- Inverted steel “T” beams supporting the panels were connected to ceiling by steel rods.
- The rods were connected to plates on the tunnel ceiling, which were secured by two adhesive anchors.

# Anchor/Panel Design

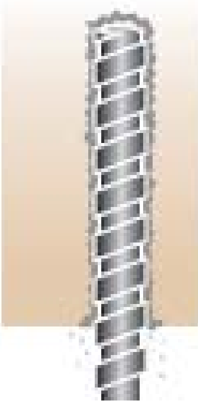


# Adhesive Anchor Detail

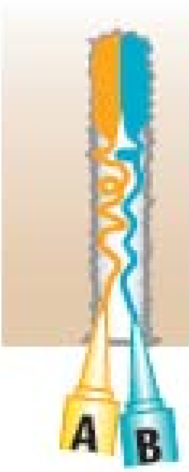


## HOW THE PROCESS SHOULD WORK



**1.** Holes drilled in reinforced concrete.

Holes should be cleaned before epoxy is applied.

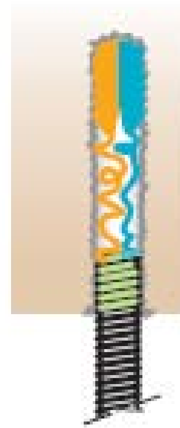



**2.** Resin and hardener applied separately into drilled hole.

Drilling holes too deep or applying too little epoxy can cause failure.

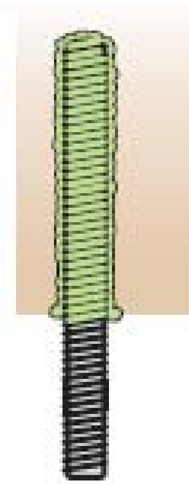
## How epoxy works

The glue used in the I-90 connector tunnel was a two-part adhesive that should harden into a tight chemical bond after components are mixed.



**3.** Screwing anchor bolt into hole mixes components.

Bolts must be clean for epoxy to adhere.



**4.** Epoxy must be given enough time to cure.

Cold weather lengthens curing time.

# Why did the ceiling panels fall?

- First drop ceilings in the Ted Williams Tunnel were built of steel and concrete supported by epoxied bolts into the tunnel roof.
- But Bechtel decided that these panels were too costly and too difficult to install.
- Decision was made to use precast panels weighing 2.5x the previous panels instead, which were cheaper and easier to install.

# But there were warnings…

- The contractor and ceiling panel designer wanted a lighter weight panel, but Bechtel refused.
- In 1996 design consultant proposed using undercut anchors that would wedge in the drilled hole in concrete (wedge anchors). but Bechtel directed that adhesive anchors be used and that previously installed wedge anchors be removed.

# Wedge Anchor in Concrete

- End of anchor expands
- Wedges against concrete
- Provides a mechanical anchorage

# More Warnings…

- Bechtel cited previous problems with wedge anchors but seemed to ignore potential problems with adhesive anchors.
- In 1997, the ceiling panel designer warned Bechtel that epoxy might not be strong enough and could fail due to heat caused by a fire.
- They still preferred wedge anchors.
  *(Later, governor required them after accident.)*

# Still More Warnings..

- On 10/7/99, contractor wrote Bechtel that 5 ceiling bolts in HOV lane had started pulling out of the concrete up to 2 inches, less than 2 months after installation, after having passed a pull out test!!
- Bechtel, contractor and epoxy supplier decided that using (faster) diamond coring drill bit was incorrect since concrete hole was too smooth to give good bond to epoxy
- The coring also left a residue that was not cleaned for 1 week, and by then, was difficult to remove resulting in bond that may have been 20% less.

## *But there were warnings from 5 years before..*

- Back in 1994, in the Ted Williams Tunnel some bolts had begun to creep out of holes.
- Bechtel quickly required that all work should cease until the problem was solved.
- However, when the concerns were raised about the bolts in the connector tunnel (where the accident later occurred), Bechtel took 3 months to reach a decision.
- During that time, contractor installed most of the bolts in the ceiling!!

- Bechtel’s decision was to begin testing the bolts for a load of 6,350 lbs instead of the 3,250 lbs. that they had been using.
- Contractor informed Bechtel that since nearly all the ceiling panels had been installed, that it would cost over $600,000 to remove or shore up the panels to test the bolts.
- Bechtel made the questionable decision to test only the bolts in the HOV lane. “if no bolts fail here at the higher loads, the other lanes will probably not require testing.”

- Over the next 8 months, 187 bolts were tested in the HOV lane—19 pulled out.
- Since 17 were in the "mock up" area where the workers made their first installation, Bechtel rationalized that workers were inexperienced with using the epoxy and that the problem no longer existed.

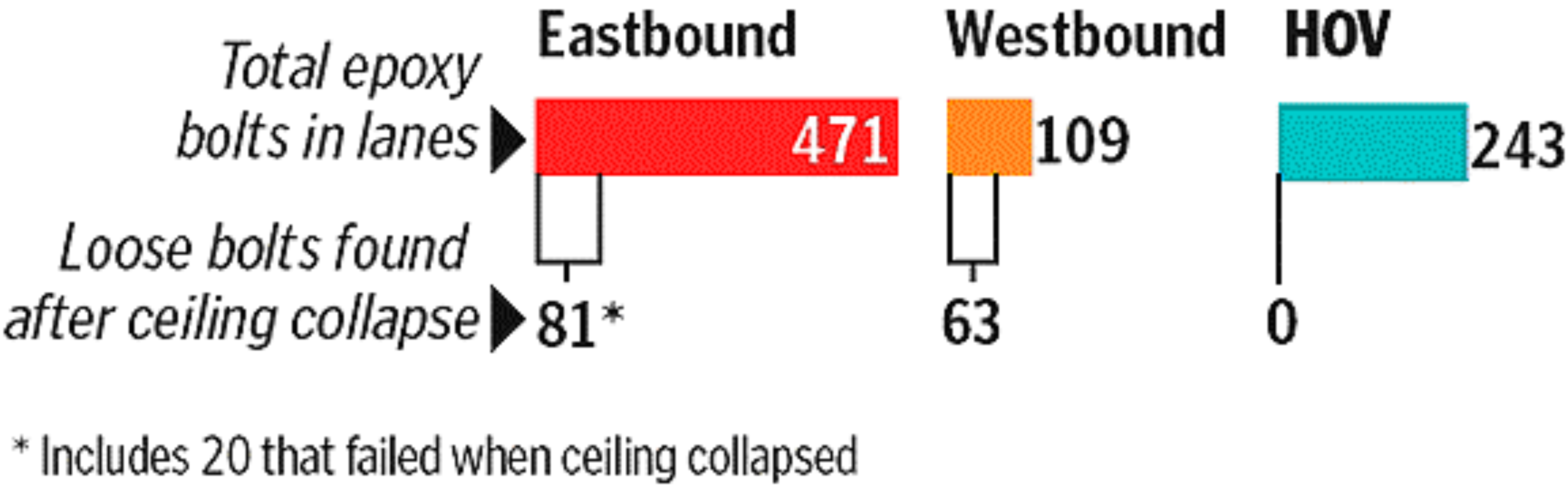
# Some post-collapse findings

- After the collapse, many other details emerged.
- It was found that over 200 bolts had come loose in the tunnel but <u>none</u> in the HOV lane.

Does testing help or not?

# Result of pull out tests

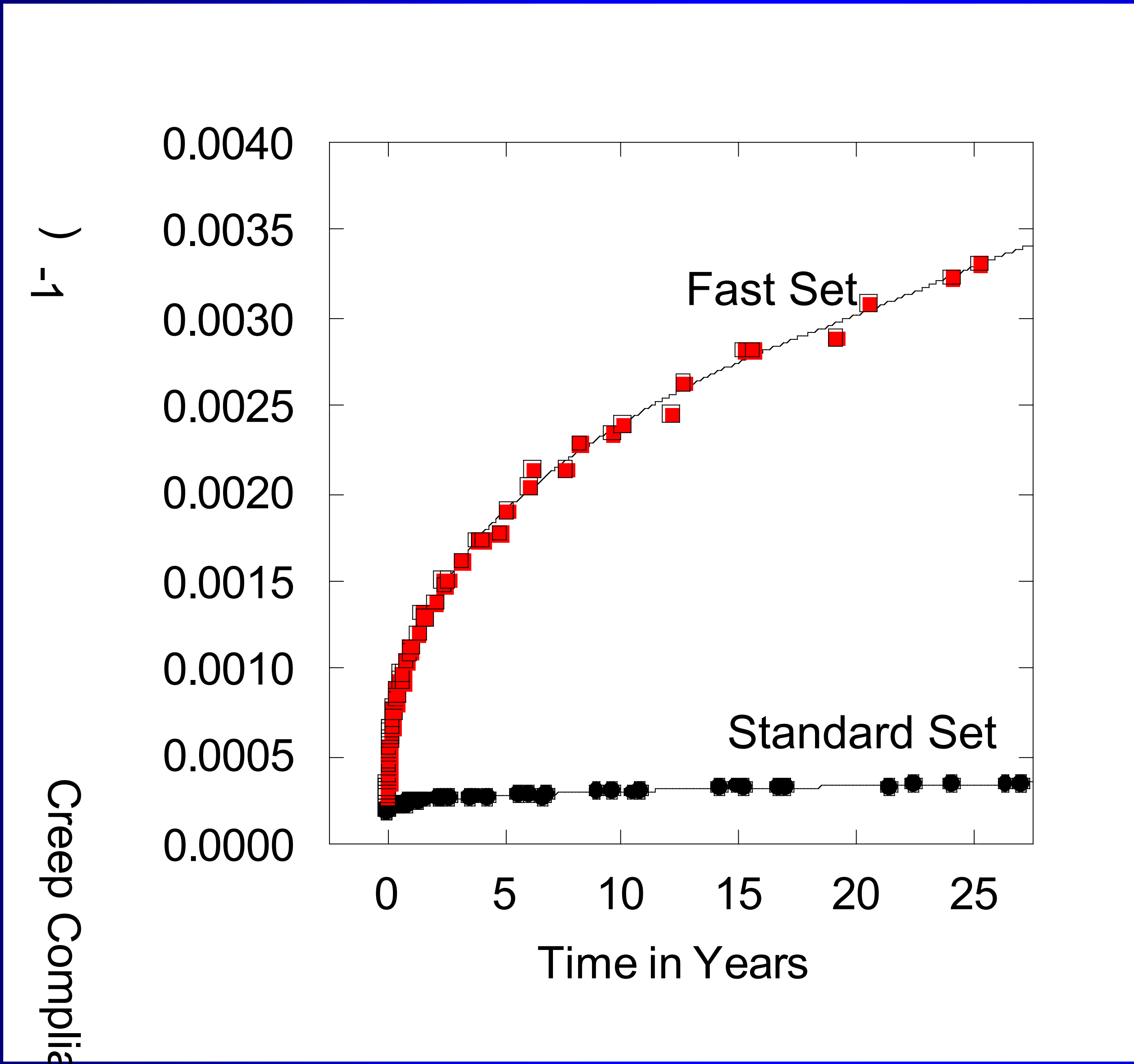
Bolts in the HOV lane were tested to hold 6,350 pounds, nearly twice the amount for bolts in the eastbound and westbound lanes.



# Epoxy Used in Tunnel

- Originally, Power-Fast Epoxy was specified.
- But for some reason the Fast Set version was used in nearly all fastener installations.

- Tests performed in 1995 and 1996 showed that Fast Set failed to meet the standard for creep, although the standard epoxy did.
- The manufacturer knew that this epoxy was being used in the tunnel, but never communicated the potential problem to the contractor nor even that the Fast Set was being used instead of the standard epoxy.



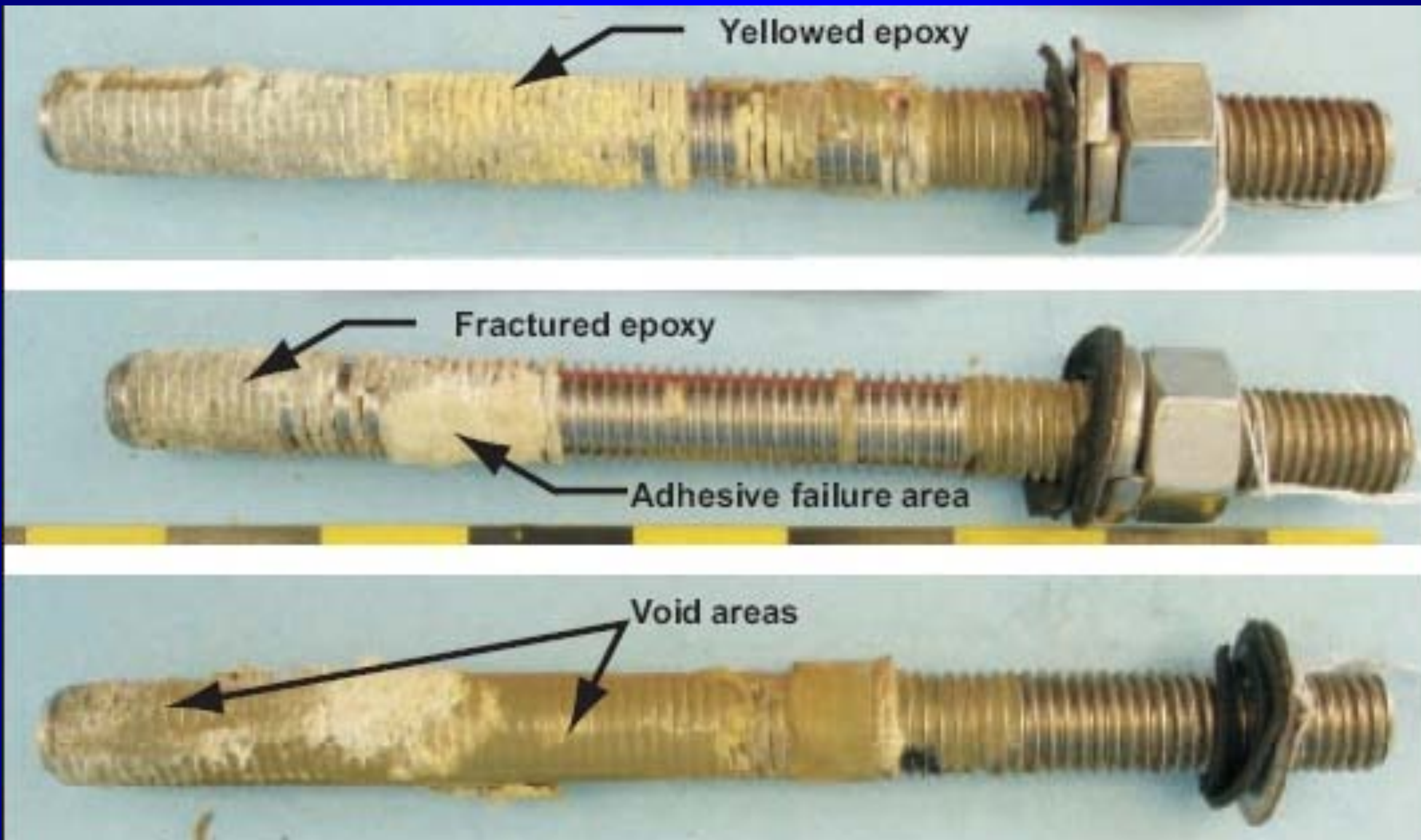

Increasing anchor displacement

Data courtesy of NIST

# Incorrect Installation

- Even in 1999, it was discovered when a “pulled-out” bolt was removed, that most of the bolt was bare - not enough epoxy - and the epoxy on the tip was brittle and easily crumbled.
- The holes had not been fully filled with epoxy.
- It was determined that this could have caused a loss of up to 38% of the pull out capacity
- Also found that dust had adhered to the bolt, affecting bond.

# Failed Adhesive Anchors



# Epoxy Voids

Seal plug position

# Summary of Anchor Issues

- Use of adhesive rather than undercut anchors
- Adhesive material selected without regard to sustained load capability—fast setting was used
- Drilling method – diamond coring
- Hole cleaning – delayed 1 week
- Voids along adhesive anchors that failed
- No follow up periodic inspections of adhesive anchors.

# Probable Cause

The National Transportation Safety Board determined that the probable cause of the July 10, 2006 ceiling collapse was the use of an epoxy anchor adhesive with poor creep resistance, that is, an epoxy formulation that was not capable of sustaining long-term loads.

# So what has been learned?

- Money often drives important decisions that affect safety.
- Ample warnings were ignored - probably because of money.
- Sound engineering principles were not followed.
- Details are important!
- Sound ethical principles were not followed.

# Primary References


- "Ceiling Collapse in the Interstate 90 Connector Tunnel, Boston, Massachusetts, July 10, 2006
- National Transportation Safety Board Accident Report HTSB/HAR-07/02, PB2007-916203
- Several articles from the Boston Globe
- Slides from Richard Wollmerhauser, Consultant and formerly of Hilti Inc.