PE

ENGINEERING FAILURE ANALYSIS & ROOT CAUSE INVESTIGATION

4 CEH

PERTINENT

BuilderCE

PROFESSIONAL ENGINEERING CONTINUING EDUCATION

Engineering Failure Analysis & Root Cause Investigation

Infrastructure, Construction & Corrective Action

Self-Paced Course Study Guide



Illustrative field documentation of pavement distress. This is a contextual illustration, not a documented incident.

COURSE	CREDIT	INSTRUCTOR
ENG-003	4 CEH / PDH · Pertinent to Engineering	James Barber, P.E.

Civil, transportation and construction engineering practice.

Superior Learning, LLC d/b/a BuilderCE

Course overview

Course description

This 4-CEH course presents a structured civil-engineering approach to investigating infrastructure and construction failures, identifying causal factors, determining root causes, and developing corrective actions. The course treats failure broadly: not only collapse or sudden loss of capacity, but also structural or geotechnical distress, serviceability problems, premature deterioration, construction nonconformance, recurring defects, drainage or hydraulic deficiencies, field incidents, and performance that falls short of a defined requirement. The emphasis is on evidence-based engineering judgment. Learners move from an observed adverse condition to a defensible explanation by preserving field evidence, reconstructing project history, testing competing hypotheses, distinguishing mechanism from cause, identifying failed controls, and connecting verified causes to corrective action.

Course positioning

The course is framed for civil, transportation, and construction engineering practice. It focuses on the investigation itself: defining the problem, developing facts, reasoning from evidence, selecting causal-analysis tools, making technically supportable dispositions, and preventing recurrence. Quality systems, document control, design changes, reliability and project controls enter the discussion when they provide evidence or explain a failed control. The scope does not include detailed metallurgical fracture analysis, rotating machinery, electronics, product forensics or litigation-oriented expert testimony.

Target audience

The course is designed for professional engineers and other engineering professionals involved in civil infrastructure design, transportation, structures, geotechnical work, construction engineering, construction engineering and inspection (CEI), public works, municipal engineering, water resources, project delivery, maintenance, quality, or technical investigations. The examples are written so that a civil engineer can apply the method to roadways, earthwork, drainage, retaining systems, concrete and structural work, utilities, temporary works, and multidisciplinary construction interfaces. The framework is also useful to owners and agency engineers who must decide what evidence is adequate, what engineering review is required, and whether corrective actions actually address the conditions that produced the problem.

Learning objectives

- Distinguish among a civil-engineering failure symptom, performance deficiency, failure mode or mechanism, proximate cause, contributing factor, failed control, root cause, and systemic cause.
- Plan a civil infrastructure or construction investigation that preserves relevant field conditions, project records, test data, photographs, measurements, survey information, and other evidence.
- Evaluate design assumptions, site and subsurface conditions, materials, drainage, construction means and methods, temporary works, sequencing, workmanship, inspection, testing, changes, operations, and maintenance as potential causal contributors.
- Apply chronology/event analysis, five-whys questioning, cause-and-effect analysis, change analysis, fault-tree logic, barrier/control analysis, and evidence-based hypothesis testing without forcing every event into one method.
- Evaluate nonconforming work and distinguish immediate containment, correction, engineering disposition, corrective action, preventive action, and effectiveness verification.
- Develop corrective actions that address verified causes while considering constructability, secondary risk, inspection and acceptance requirements, and recurrence prevention.
- Document investigation scope, evidence, analysis, uncertainty, conclusions, corrective actions, and lessons learned in a technically defensible professional-engineering record.

Six-module instructional plan

MODULE	MINUTES	FOCUS
Civil Infrastructure Failure Investigation Framework	35	Framework / application
Field Evidence, Project Records & Fact Development	45	Evidence / technical analysis
Technical Causal Analysis in Civil Engineering	45	Evidence / technical analysis
Root-Cause Tools Adapted to Civil Projects	40	Analysis / action
Nonconforming Work, Corrective Action & Recurrence Prevention	40	Analysis / action
Applied Civil Case Scenarios, Lessons Learned & Professional Documentation	35	Framework / application

How to complete this course

Read all modules in this course and study the case examples. No separate module acknowledgement is required. When you have finished reading, select Continue at the bottom of the BuilderCE lesson page to begin the 10-question final examination. If you are reading the PDF, return to that webpage first. A score of at least 70% is required to pass. Retakes are permitted.

The 240-minute allocation is an instructional plan. Individual reading and application time may vary.

I-35W case evidence · Glossary · Principal references

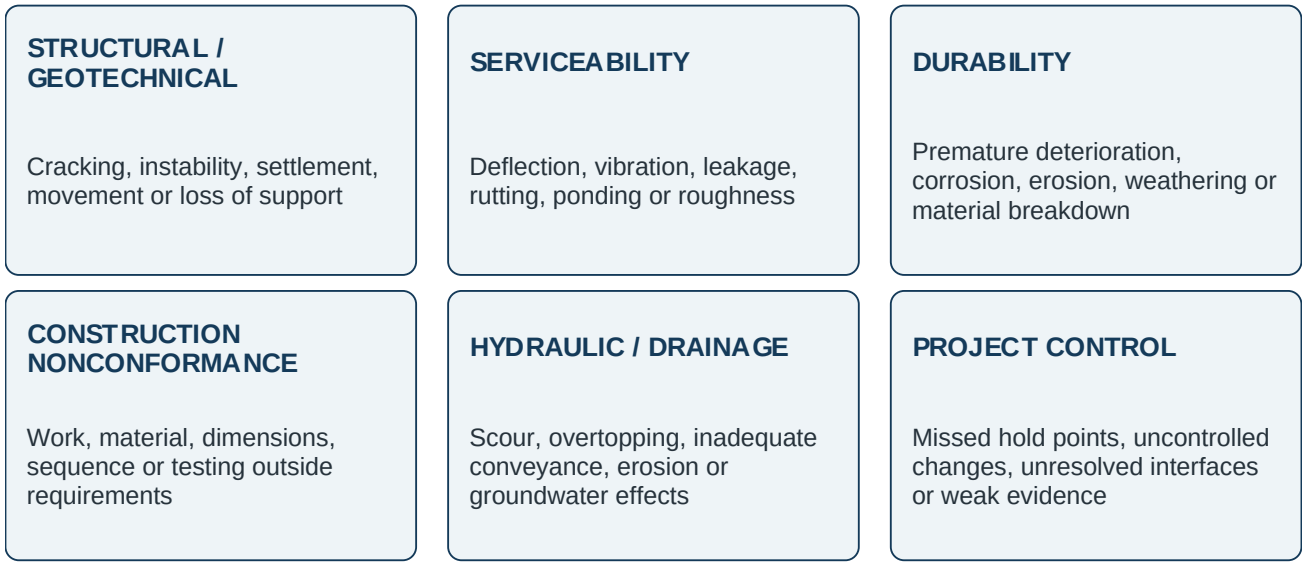


Figure 1. Civil failure includes performance departures, nonconformance, deterioration, hydraulic deficiencies, and project-control breakdowns - not only collapse.

MODULE 1

Civil Infrastructure Failure Investigation Framework

Instructional allocation: 35 minutes

> **Module purpose.** Define the failure correctly, stabilize the condition, preserve evidence, control scope, and avoid bias before causal analysis begins.

1.1 Failure in civil practice is a departure from a defined requirement

Civil engineers investigate many conditions that are serious without being catastrophic. A retaining wall may move beyond an allowable tolerance while remaining stable. A pavement may rut and crack years before its intended service life. A drainage system may repeatedly pond even though no pipe has physically broken. Concrete may fail an acceptance test while later core results suggest adequate in-place strength. Earthwork may settle after acceptance. A temporary support system may experience unexpected movement without collapsing. In each case, the visible condition is important, but the investigation becomes useful only when the engineer defines the performance requirement that was not met and the evidence needed to explain the departure.

A practical definition of failure for this course is any adverse condition in which an engineered system, component, material, construction process, or project control does not perform as required or intended. The requirement may come from sealed design documents, project specifications, approved submittals, a governing code, an agency standard, a contract acceptance criterion, a permit condition, or an engineering performance objective. This framing prevents the word failure from becoming dramatic but vague. It also keeps the investigation anchored to measurable expectations. Before asking why a condition occurred, the engineer should be able to state what was expected, what actually occurred, and how the two differ.

The distinction matters because civil projects contain variability. Soil properties vary spatially. Material test results vary. Weather changes. Construction sequence shifts. Existing utilities are not always where the record drawings indicate. A small deviation does not automatically represent engineering failure, and a large visual defect does not automatically reveal the mechanism that produced it. The investigator must first determine whether the condition is outside the applicable tolerance, acceptance criterion, serviceability limit, safety margin, durability expectation, or contractual requirement. Only then can the scope of the causal investigation be proportional to the consequence.

1.2 Symptom, mechanism, cause, and control failure are different questions

Investigations become confused when the same word is used for different levels of explanation. A crack is usually a symptom. Differential movement may be the mechanism creating the crack. Saturated support, inadequate joint detailing, restrained shrinkage, thermal movement, settlement, or a load concentration may be contributing causes depending on the context. A missed drainage detail, inadequate field verification, an uncontrolled change, or failure to react to monitoring data may explain why the causal condition existed or escaped control. These are related but not interchangeable conclusions.

A useful sequence is to ask four separate questions. First: What happened? This is the observed condition and event history. Second: How did the physical or functional system depart from its intended performance? This is the mechanism. Third: Which technical, environmental, construction, human, or organizational conditions contributed to that mechanism? Fourth: Why did the project controls not prevent, detect, or correct those conditions before they produced the adverse outcome? The investigation should progress through these layers rather than jumping directly from a symptom to a person, procedure, or broad label such as poor workmanship.

For example, if a roadway develops localized settlement, the mechanism may be loss of support and densification under loading. Contributing conditions could include high moisture, inadequate compaction, unsuitable material, buried debris, a trench backfill interface, or a leaking utility. If density tests were recorded as acceptable, the investigation may need to examine whether the tested locations

represented the failed area, whether the test method was appropriate, whether the lift thickness changed, whether later excavation disturbed the support, or whether drainage conditions changed after testing. The root-cause analysis is strongest when it explains both the physical mechanism and the control path that allowed it.

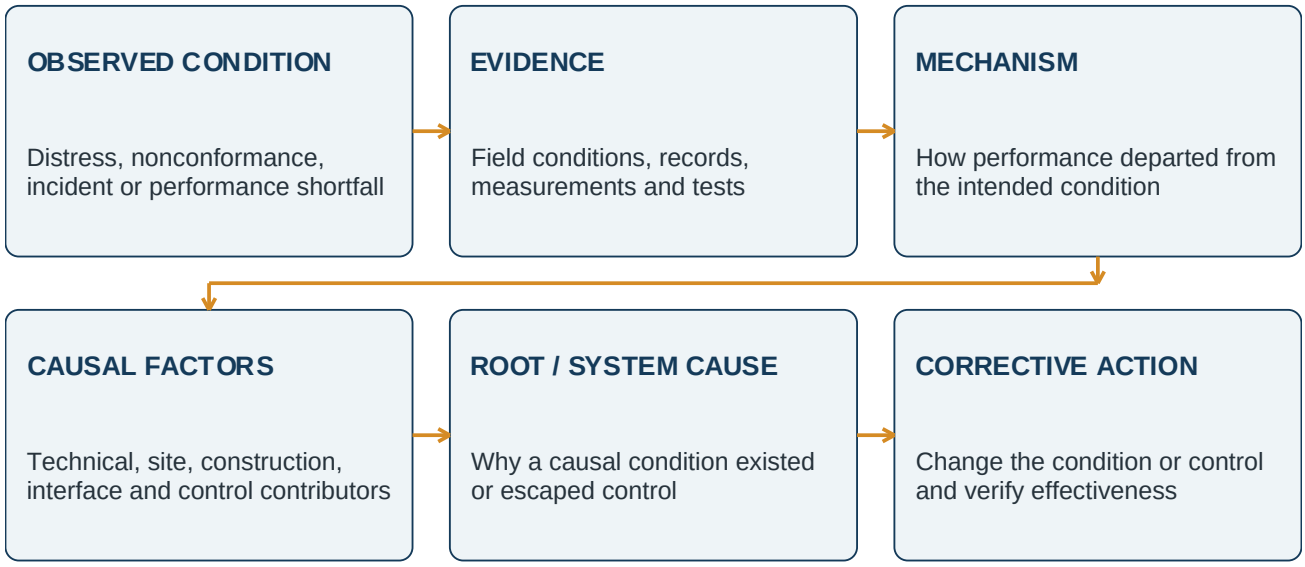


Figure 2. A defensible investigation connects the observed condition to evidence, mechanism, causal factors, root or systemic causes, corrective action, and verified effectiveness.

1.3 Immediate response: protect people, stabilize the condition, and preserve evidence

Before causal analysis begins, the engineer may need to support immediate decisions about safety and continuity of operations. Civil failures can create unstable excavations, falling-object hazards, compromised traffic barriers, undermined pavement, overloaded temporary supports, exposed utilities, hydraulic hazards, or damaged structural elements. The first priority is to manage the immediate risk using the authority and procedures applicable to the project. Access restrictions, shoring, traffic control, temporary bracing, dewatering, load restrictions, monitoring, or emergency repairs may be needed before a detailed investigation can proceed.

Emergency action can unintentionally destroy evidence. Demolishing a distressed element, excavating a failed embankment, pumping water from a site, removing damaged temporary works, resurfacing failed pavement, or replacing a utility can erase the physical relationships needed to understand the event. When conditions allow, the team should document the scene before alteration. Photographs should include overall context, intermediate views, and close details with scale. Survey control, elevations, crack widths, offsets, dimensions, material locations, water levels, and visible sequence information should be captured. Samples and removed components should be identified so that later testing can be related to the original location.

Preservation does not mean delaying an action that is necessary for public safety. It means integrating evidence capture into the response. Even a fast-moving field situation benefits from a short preservation checklist: what must be photographed, what should be surveyed, which records should be secured, what material should be retained, who observed the condition before alteration, and which decisions must be time-stamped. The investigation record should clearly distinguish the pre-response condition from changes introduced by stabilization or repair.

1.4 Define a neutral problem statement before selecting a cause

A good problem statement describes the adverse condition without embedding an unproven cause. 'Wall failure caused by inadequate drainage' is a conclusion disguised as a problem statement. A more neutral version is: 'Between Stations 24+00 and 24+80, the wall moved outward up to 1.8 inches relative to baseline survey control after completion of backfill, with movement concentrated near the low-point

drainage outlet.' The second statement tells the team what needs explanation and identifies useful dimensions, location, and timing without foreclosing competing hypotheses.

The initial statement should answer what, where, when, and how much to the extent known. It should also identify the decision the investigation must support. Is the owner deciding whether to reopen traffic? Is the engineer of record deciding whether a repair is adequate? Is the agency determining the extent of a nonconforming lot? Is the contractor evaluating whether the same defect could exist elsewhere? Is the project team deciding whether a design change or quality-control change is required? The decision need affects the investigation scope and the level of certainty required.

Scope control is especially important in civil work because a visible problem can expand into an unlimited review of the entire project. The engineer should define the initial geographic limits, time period, system boundaries, and interfaces to be examined, while remaining willing to expand them if evidence indicates a broader condition. The scope should also identify what is outside the investigation unless later evidence makes it relevant. Clear boundaries improve both technical efficiency and the defensibility of conclusions.

1.5 Build the investigation team around the interfaces that matter

Civil failures often occur at interfaces: geotechnical information must be translated into design assumptions; design must be translated into details and specifications; details must be translated into submittals, means and methods, and field sequence; construction must be verified through inspection and testing; and the completed asset must be operated and maintained in a way consistent with the design basis. An investigation may therefore require input from the engineer of record, specialty engineer, geotechnical engineer, contractor, subcontractor, CEI staff, laboratory, surveyor, materials supplier, owner, maintenance personnel, or a specialist who was not part of the original project.

The investigation lead should distinguish technical participation from decision authority. A contractor may provide essential sequence and means-and-methods information without having authority to accept a design deviation. A testing laboratory may explain results without deciding the engineering disposition. An inspector may document what was observed without possessing the full design basis. The engineer of record may have authority over design intent but may need independent specialty input for geotechnical, materials, structural, or forensic testing. Clear roles reduce the risk that the final conclusion simply reflects the perspective of the most influential participant.

Independence does not necessarily require an outside consultant for every event, but the team should recognize conflicts and cognitive pressure. An engineer reviewing his or her own prior decision may be capable of objective analysis, yet the investigation plan should still include checks that challenge assumptions. For higher-consequence events, independent review of the evidence, calculations, or causal logic may be warranted. The goal is not to assign blame; it is to improve confidence that the explanation survives scrutiny.

1.6 Bias control is an engineering quality issue

Failure investigations are fertile ground for hindsight bias. Once the outcome is known, earlier project records can appear to contain obvious warnings that were not obvious at the time. Confirmation bias can then cause the team to collect mainly the facts that support an early theory. Availability bias favors familiar causes such as 'poor compaction' or 'bad concrete' even when the evidence is incomplete. Outcome bias judges the reasonableness of a prior decision mainly by the later result rather than by the information available when the decision was made.

The best defense is procedural. Write the initial hypotheses down. Identify what evidence would support each one and what evidence would contradict it. Assign someone to challenge the leading explanation. Preserve negative evidence: conditions that should exist if a hypothesis were true but are absent. Record changes to the theory as evidence develops. Use tables or matrices when the issue is complex enough that memory becomes unreliable. The discipline is similar to a design check: the engineer makes the reasoning inspectable.

Professional judgment remains essential. Root-cause tools do not convert uncertain civil conditions into mathematical certainty. The investigator should state the basis and limits of judgment, especially when

evidence is missing, the scene has been altered, subsurface conditions cannot be fully reconstructed, or several causes interacted. A technically responsible report may conclude that the evidence supports multiple contributing causes and does not support a single exclusive root cause. That is stronger than overstating certainty simply to produce a neat answer.

1.7 Applied practice: an early investigation screen

Consider a newly reconstructed intersection where localized pavement depression and cracking appear around a utility crossing after several weeks of heavy rain. A weak investigation would begin with the conclusion that the trench was poorly compacted. A stronger screen would identify the requirement and observed geometry, capture elevations and distress limits, review utility backfill records, compare adjacent density results, inspect drainage paths, check whether later utility work disturbed the area, review rainfall and ponding history, and compare the failed location with similar utility crossings that performed well. The team might still conclude that backfill compaction was a major cause, but the conclusion would be built from evidence rather than pattern recognition.

The screening phase should end with a short plan: immediate risk controls, evidence to preserve, records to collect, field measurements to obtain, initial hypotheses to test, responsible participants, and the decision deadline. This plan can be one page for a moderate field issue or much more detailed for a high-consequence event. The important point is that the investigation becomes intentional before excavation, repair, or schedule pressure changes the condition.

Module 1 - Key points

- Define failure against an applicable requirement before discussing cause.
- Separate the observed condition, physical mechanism, contributing causes, failed controls, and systemic causes.
- Integrate immediate safety/stabilization decisions with evidence preservation.
- Use a neutral problem statement and control the investigation scope.
- Design the team and review process to challenge early assumptions rather than reinforce them.

MODULE 2

Field Evidence, Project Records & Fact Development

Instructional allocation: 45 minutes

> **Module purpose.** Build a fact base from field condition, design records, construction history, quality records, environment, operations, interviews, and uncertainty.

2.1 Start with an evidence strategy, not a document dump

Civil projects generate enormous records. An investigation can therefore fail in two opposite ways: too little evidence is preserved, or the team collects thousands of files without a strategy for deciding what matters. An evidence plan connects each investigation question to specific sources. If the question is whether differential settlement caused cracking, relevant evidence may include baseline and current survey data, subgrade or foundation information, fill placement records, moisture conditions, compaction records, structural details, crack mapping, and loading history. If the question is whether an uncontrolled field change contributed, the evidence plan may focus on RFIs, sketches, change directives, submittal revisions, daily reports, photographs, and approval dates.

The plan should distinguish primary evidence from explanatory context. Primary evidence directly describes the condition, requirement, sequence, measurement, test, or decision. Explanatory documents help interpret that evidence but should not replace it. For example, a project meeting note stating that 'density was good' is less direct than the actual density-test reports with locations, dates, lift information, and results. A recollection that 'the outlet was open' is weaker than dated photographs or inspection

notes. The investigator should seek the most contemporaneous and specific evidence reasonably available.

Evidence relevance also changes as the theory develops. An initial broad set of records may reveal a change in material source, an unexpected groundwater condition, or a revised sequence that justifies targeted follow-up. The evidence plan should therefore be treated as a controlled working document. Add sources when new questions emerge, document unavailable records, and note when the investigation relies on secondary or reconstructed information because primary evidence no longer exists.

2.2 Document field condition so another engineer can reconstruct it

Field observation is more than taking photographs. A condition survey should establish orientation, location, scale, extent, severity, and pattern. Distress mapping can reveal whether cracks align with joints, utility trenches, support transitions, drainage paths, construction stages, or structural details. Survey data can distinguish global movement from local deformation. Elevation profiles can show whether settlement is progressive, localized, or tied to a transition. Repeated measurements can establish rate, which is often more important than a single magnitude.

Photographs should be deliberate. Begin with context views that show the overall relationship of the failed area to the project. Add intermediate views that identify individual components or zones. Then add close views with a scale or reference. Photograph labels, stationing, grid lines, specimen IDs, reinforcing details, drainage outlets, joint locations, temporary supports, and interfaces. The file name or photo log should preserve date, location, orientation, and photographer. When geometry matters, photographs should supplement rather than replace measurements.

For cracking or movement, a simple condition map can be more informative than dozens of isolated images. Record crack orientation, width, length, displacement, spalling, leakage, rust staining, heave, settlement, or other visible indicators. If monitoring is installed, record sensor type, location, datum, precision, reading frequency, and environmental conditions. A graph without trustworthy reference control may create false confidence. The investigation should be able to explain what each measurement represents and how it can be compared over time.

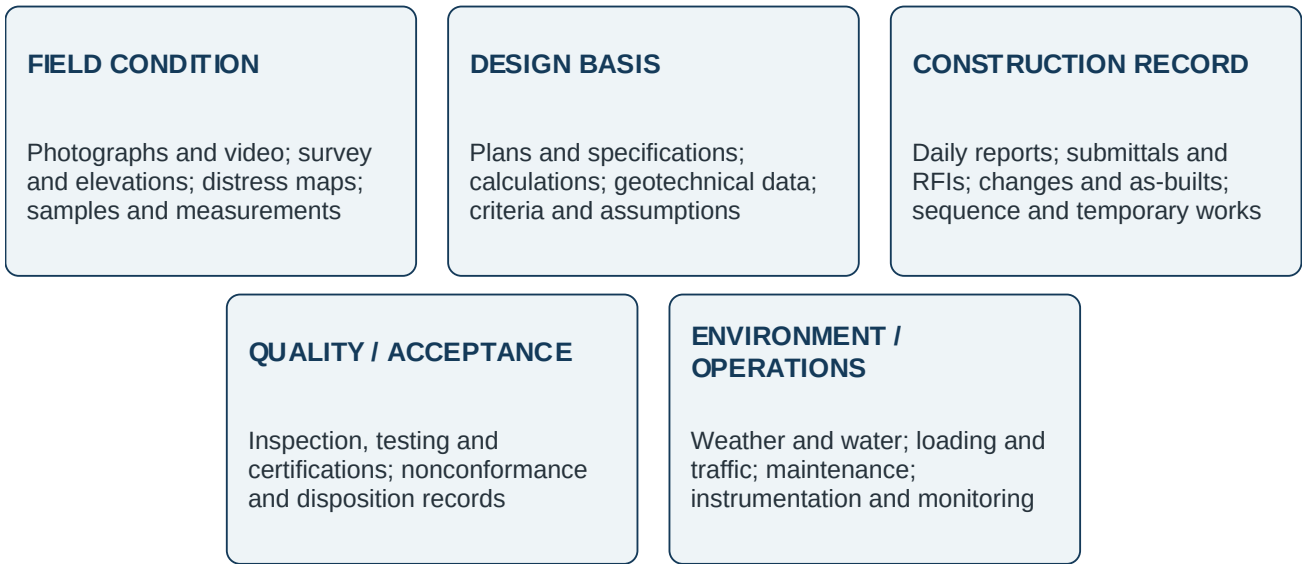


Figure 3. An evidence map integrates field condition, design basis, construction records, quality/acceptance evidence, and environment/operations.

2.3 Design records reveal the intended performance model

Plans and specifications show more than contractual requirements; they reveal what the design expected the system to do. Calculations, design criteria, geotechnical reports, drainage studies, modeling assumptions, design memoranda, and review comments may be necessary to understand the

intended load path, support condition, tolerance, sequence dependency, durability strategy, or hydraulic performance. A failure investigation should identify the particular assumptions that matter instead of re-reviewing the entire design without focus.

Assumptions deserve special attention because civil design inevitably simplifies variable field conditions. A geotechnical report may define groundwater observations at discrete times and locations. A retaining-wall analysis may assume drainage is functional. A pavement design may assume a support value and drainage condition. A structure may rely on a construction sequence or temporary bracing until continuity is achieved. A utility relocation may depend on field verification before excavation. The investigation should compare these assumptions with actual project conditions and determine whether differences are normal variability, an unrecognized change, or a contributor to the adverse outcome.

Design records can also reveal unresolved questions. Review comments, value-engineering proposals, alternative details, delegated-design interfaces, and coordination notes may show that a risk was recognized but handled differently than the final record suggests. The investigator should avoid implying that the existence of a comment proves causation. Instead, treat it as a pointer to a technical issue that should be tested against field evidence.



Illustrative field investigation: drainage and erosion conditions at a culvert are documented before stabilization or repair alters the hydraulic evidence. This is a contextual illustration, not a documented incident.

2.4 Construction records reconstruct what was actually built and in what order

Civil work is sequence-sensitive. Excavation changes support. Dewatering changes groundwater conditions. Backfill creates load. Temporary shoring carries loads before permanent systems engage. Concrete strength develops with time. Pavement layers depend on support and moisture conditions at placement. Traffic staging can introduce loads before final construction is complete. Daily reports, look-ahead schedules, inspection notes, photographs, equipment records, delivery tickets, submittals, work plans, and as-built information help reconstruct these conditions.

A useful timeline includes both physical work and information flow. When was a shop drawing approved? When was the related work installed? When did an RFI identify a field conflict? When was the response issued? Did the crew proceed before the response? When did a test result become available? When was a deficiency first observed? When was the engineer notified? When did a change become formal? These time relationships often explain why a control that existed on paper did not influence the field condition.

Temporary works deserve explicit attention because they may not be fully represented on permanent design drawings. Formwork, shoring, bracing, erection procedures, excavation support, dewatering systems, temporary drainage, falsework, work platforms, and staged loading can be central to the event. The investigation should identify the responsible design or means-and-methods documents, review status, field changes, and actual sequence without automatically assuming those responsibilities belong to the engineer of record.

FACT	Measured settlement: 1.4 in. at Grid C after placement
OBSERVATION	Movement concentrated near the new-fill transition
INTERPRETATION	Differential support may contribute to the distortion
HYPOTHESIS	Inadequate compaction and wet subgrade may explain the settlement
CONCLUSION	Accept only after testing competing explanations against evidence

Figure 4. Keep facts, observations, interpretations, hypotheses, and conclusions at distinct levels of certainty.

2.5 Quality and acceptance records are evidence of control performance

Inspection and testing records help answer two different questions: what was the condition of the work, and how effectively did the project controls detect and respond to variation. The investigation may review material certifications, concrete tests, soil and aggregate tests, asphalt data, nondestructive testing, weld inspection, survey checks, density results, sampling locations, inspector reports, punch lists, nonconformance reports, and acceptance documentation. The objective here is not to re-teach QA/QC systems. It is to determine what the records establish, what they do not establish, and whether the control system functioned as intended for the failed condition.

Sampling is especially important. A passing test does not prove that every location conforms. The investigator should ask whether the sample location, frequency, method, timing, and represented lot are relevant to the failed area. A failed test likewise does not automatically prove the observed failure mechanism. Traceability matters: which material, lift, batch, station, structural placement, or production period did the result represent? Were retests or corrective actions performed? Did the acceptance decision incorporate all available data or only the most favorable result?

Inspection records should be read in context. A checked box can prove that a record was completed but may provide little evidence of what was actually observed. Detailed notes, measurements, photographs, hold-point releases, and documented resolution often have more investigative value. Conversely, the absence of a record does not automatically prove the underlying activity was omitted. The investigator should state what the record supports and avoid converting documentation weakness into a physical-cause conclusion without additional evidence.

2.6 Environmental, hydraulic, and operational history can change the meaning of field data

Civil infrastructure operates in an environment that changes over time. Rainfall, groundwater, tidal variation, storm surge, freeze-thaw in some regions, heat, drought, scour, erosion, construction dewatering, pumping, traffic loading, vibration, adjacent excavation, and utility leaks can influence performance. The investigation should identify the environmental variables that are mechanically relevant to the suspected mechanism rather than adding weather history simply because it is available.

Time alignment is critical. If wall movement accelerated after a rainfall event, the team should determine whether groundwater or pore-pressure data exist, whether drains were functional, whether backfill was complete, and whether monitoring shows movement before the event. If pavement distress appears after a wet season, the investigator should compare rainfall with drainage condition, support moisture, construction sequence, and traffic. A correlation in time can generate a hypothesis, but it does not establish causation without a plausible mechanism and supporting evidence.

Operational and maintenance records may be equally important after construction. Drainage systems clog. Joints lose seals. Loads change. Unauthorized cuts or attachments are installed. A roadway receives heavier traffic than assumed. A pump station settlement problem may be influenced by groundwater drawdown. The investigator should understand how the asset was actually used and maintained, while distinguishing post-construction changes from conditions present at acceptance.

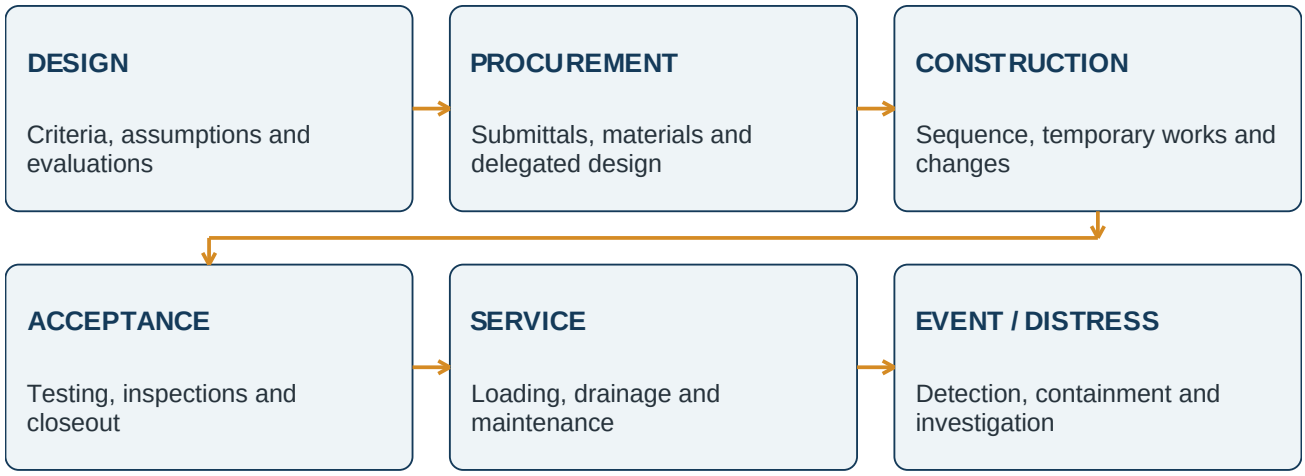


Figure 5. A project-lifecycle timeline helps identify when causal conditions entered the work and when controls should have detected them.

2.7 Interviews fill gaps, but memories are not measurements

Interviews are valuable for reconstructing sequence, intent, undocumented field conditions, and decision context. They are also vulnerable to memory error, hindsight, role-based perspective, and social pressure. The investigator should use open questions first: What did you observe? What happened next? Which drawing or instruction were you using? When did you become aware of the condition? What action did you take? Which record would document that decision? Leading questions that embed the suspected cause should be avoided when possible.

Interview information should be corroborated with contemporaneous records, photographs, messages, logs, or other witnesses when the point is material to the conclusion. Differences between recollections are not necessarily evidence of dishonesty; people may have seen different parts of the project or may be reconstructing events from incomplete memory. Record the date, participants, subject, and whether the notes are a summary or verbatim transcript. For routine internal investigations, a concise documented summary may be sufficient; high-consequence events may require more formal procedures.

The most useful interview often identifies where to look next. A superintendent may remember that the crew changed sequence because of weather. An inspector may identify a location where a test could not be performed. A designer may explain the assumption behind a detail. A maintenance worker may know that a drain repeatedly clogged. These statements become leads that should be tested against evidence rather than conclusions that replace it.



Illustrative field investigation: survey control ties pavement and utility-related observations to reproducible project coordinates and elevations. This is a contextual illustration, not a documented incident.

2.8 Build a chronology and baseline-versus-actual matrix

A chronology converts scattered project records into a sequence that can be analyzed. Start with milestones that matter to the suspected mechanism: design release, submittal approval, site preparation, excavation, dewatering, material placement, tests, inspections, changes, loading, weather events, first observation of distress, response actions, and subsequent measurements. The level of detail should match the event. A minute-by-minute timeline is unnecessary for gradual settlement, while a rapidly developing temporary-works incident may require much finer resolution.

The baseline-versus-actual matrix is a second organizing tool. For each material question, identify the expected condition and the observed condition. What elevation was required, and what was surveyed? What material property was specified, and what did the represented tests show? What groundwater condition was assumed, and what was observed? What sequence was approved or planned, and what sequence occurred? What hold point was defined, and what evidence shows it was released? The gap column then becomes a focused list of investigation questions rather than a general list of project imperfections.

The chronology and matrix should evolve together. A gap may identify a missing time relationship, and the timeline may reveal that an apparently important record occurred after the condition had already developed. This cross-checking is one reason structured fact development is more reliable than reading documents in isolation.

FIELD	BASELINE / EXPECTED	ACTUAL / OBSERVED	GAP / FOLLOW-UP
Geometry / elevation	Approved plans and control points	Surveyed condition	Quantify deviation; check survey control
Material / property	Specified class, strength or gradation	Cores and test results	Confirm lot, sampling and representativeness
Site / support	Geotechnical model and assumptions	Field logs, groundwater and proof-roll	Test the changed-condition hypothesis
Sequence / temporary works	Approved method and staging	Daily records and photos	Identify changes in sequence and approvals
Inspection / testing	Defined hold points and frequency	Performed and documented controls	Determine a missed barrier or weak evidence

Figure 6. Baseline-versus-actual comparison turns broad project review into focused investigation questions.

2.9 Manage uncertainty and evidence gaps explicitly

Every civil investigation has limits. The failed material may have been removed. Survey control may be uncertain. As-built records may be incomplete. Subsurface conditions may only be known from borings outside the failed zone. A test specimen may not represent the exact location. A sensor may have stopped recording before the event. The engineer should not hide these limitations in boilerplate. Each material gap should be connected to the conclusion it affects.

Uncertainty can sometimes be reduced through targeted testing, additional survey, excavation, cores, probes, laboratory analysis, monitoring, or numerical modeling. In other cases, further work has diminishing value or would damage the asset. The investigation plan should make that tradeoff visible. If two hypotheses remain plausible because a decisive piece of evidence no longer exists, the report should say so and design corrective actions that are robust to the remaining uncertainty where practicable.

A useful discipline is to assign each major finding an evidence status: directly verified, strongly supported, moderately supported, plausible but unverified, contradicted, or unresolved. These labels do not need to appear in every final report, but using them internally prevents the team from treating all statements as equally certain.

2.10 Applied evidence workshop: roadway distress near a drainage transition

Assume a reconstructed roadway develops rutting and alligator cracking over approximately 180 feet near a sag vertical curve. The distress appears within one rainy season. The first field visit identifies ponding near the curb, soft shoulder material at one location, and visible wheel-path deformation. The investigation team should resist the temptation to label the problem a drainage failure immediately. A defensible evidence plan would include surface and subsurface drainage details, current and baseline elevations, outlet condition, pavement and base thickness, density and material records, asphalt production data, proof-roll or inspection notes, rainfall and traffic history, utility crossings, construction staging, and comparison with nearby locations that received the same materials but are performing acceptably.

The team should define how each data source can change the decision. Survey may show whether the sag geometry was constructed as intended. Drainage inspection may reveal whether the outlet is blocked or undersized. Test traceability may show whether density data represent the failed zone. Cores can help characterize pavement structure but should be located to distinguish hypotheses. Comparison locations can be especially powerful: if the same material and crew performed well where drainage is different, or the same drainage detail performs well where support is different, the pattern helps prioritize

further testing. The workshop objective is not to solve the case in advance; it is to design an evidence path that can discriminate among competing explanations.

Module 2 - Key points

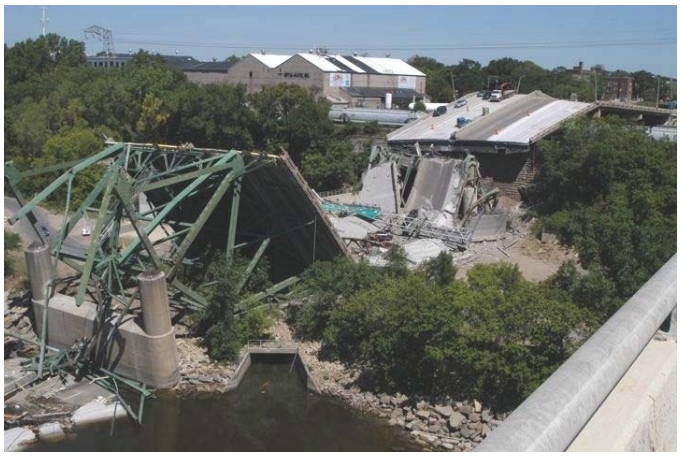
- Connect each investigation question to specific evidence sources.
- Document field geometry, pattern, scale, and rate - not just appearance.
- Use design, construction, quality, environmental, and operational records to reconstruct both condition and control performance.
- Use an event sequence and expected-versus-observed comparison to organize facts.
- State uncertainty and evidence gaps in terms of how they affect the conclusions.

Worked investigation: I-35W evidence to conclusion

A complete investigation must explain the observed failure, discriminate among plausible mechanisms and connect the supported cause to a useful control. This case follows that path using the public I-35W investigation record. The evidence register and practice-action matrix below are teaching summaries, not recovered project forms or claims that a follow-up action was completed.

Define the problem before selecting a cause

Neutral problem statement: the I-35W deck truss lost its ability to carry the loads present on August 1, 2007, and collapsed. The inquiry must locate the initiating loss of resistance, distinguish it from damage caused by the collapse and explain the demand and resistance at that location. A statement such as “corrosion caused the collapse” would assume the conclusion before the evidence was evaluated.



Documented investigation photograph. Collapsed north section; NTSB HAR-08/03, Figure 15, printed p. 20. The image locates evidence and does not establish the initiating mechanism by itself. Open source

Reconstruct the sequence

WHEN	ESTABLISHED CONDITION / EVENT	INVESTIGATIVE USE
Before the collapse	Earlier modifications increased bridge dead load.	Reconstruct permanent demand; do not use the original weight unchanged.
About 2:30 p.m., August 1	Construction equipment and aggregates were in position.	Locate the temporary demand before the collapse.
About 6:05 p.m.	The bridge collapsed; surveillance video captured part of the sequence.	Compare event order with the recovered configuration.
Investigation	Physical evidence, records and structural analyses were evaluated together.	Separate initiating failure from consequential damage.
November 14, 2008	The NTSB adopted its report.	Distinguish the final finding from early speculation.

Chronology: NTSB accident summary and HAR-08/03 cover / executive summary. A sequence establishes order; it does not alone prove causation. Open source

Build an evidence register that can change the conclusion

RECORD	RESULT / INTERPRETATION	CONCLUSION IT TESTS
E1 · Video and recovered configuration	NTSB located initiation at the L9/U10W diagonal / U10 connection.	Failure of a visibly damaged component need not be the initiating event.
E2 · Drawings and plate examination	U10 plates matched the specified design but had inadequate original capacity.	The central deficiency was design adequacy, rather than an assumed fabrication departure.
E3 · Physical examination and analyses	Recovered structure, finite element analyses and video did not support corrosion or floor-truss fracture as initiators.	A plausible deterioration mechanism must survive the case-specific evidence.
E4 · Modification and construction records	Permanent changes and localized temporary loading entered the demand reconstruction.	The demand history and connection resistance must be evaluated together.

Evidence register: teaching synthesis of HAR-08/03, findings 1–3, 6–8 and 16, printed pp. 149–150. Consult the report for the underlying analyses and their limitations. Open source

Test alternatives instead of defending the first theory

CANDIDATE EXPLANATION	DISPOSITION FROM THE RECORD	REASONING LESSON
Corrosion or preexisting cracking initiated failure	Not causal or contributory in the NTSB findings.	Observed damage and a credible general mechanism are insufficient without the correct location and sequence.
Floor-truss fracture, temperature or pier movement	Excluded as causes or contributors by the investigation.	Use the reconstruction to reject alternatives; do not reject them because they seem less familiar.
Construction loading alone explains the loss	Incomplete: the final finding combines loading with deficient U10 capacity.	Avoid replacing a resistance problem with a load-only explanation.
Bowing occurred only during collapse	Precollapse photographs showed distortion. Its precise origin remained unresolved.	An unresolved subsidiary question does not erase a supported principal finding.

Alternative dispositions: HAR-08/03, findings 3, 6, 16 and 20, printed pp. 149–151. These exclusions apply to this event, not to all bridge failures. Open source

Separate mechanism, loading and failed controls

The NTSB attributed the collapse to inadequate U10 gusset-plate capacity caused by a design error, acting with increased bridge dead load, traffic and concentrated construction loading. Its finding also identified deficiencies in design checking and review, attention to plate distortion and inclusion of connections in load ratings. This connects a physical failure to the controls that should have prevented or detected the weakness.

Final causal finding: NTSB accident summary, “What We Found”; HAR-08/03, printed p. 152. Open source

The evidence changes the recommendation. If the explanation stopped at “old bridge” or “heavy stockpile,” the response might emphasize appearance or material placement alone. A connection-capacity finding requires the load path to include its connections and requires changes in demand to be checked against that resistance. The evidence trail should remain visible from each factual input to the model, conclusion and action.

Turn the finding into a verifiable action

FHWA Technical Advisory T 5140.29, issued January 15, 2008, recommended checking gusset-plate capacity in initial ratings and relevant recalculations of non-load-path-redundant steel truss bridges. This is a documented historical response. Its date precedes the final report; it must not be portrayed as proof that every later recommendation was implemented.

Historical action: FHWA T 5140.29. Use currently applicable bridge requirements for actual work. Open source

PRACTICE ACTION FOR AN ANALOGOUS PROJECT	RECORD NEEDED	ACCEPTANCE / EFFECTIVENESS CHECK
Check critical connections explicitly.	Connection calculation, actual geometry and material basis, independent technical check.	The released rating covers the governing connection as well as its adjoining members.
Control changed permanent and construction loads.	Updated load inventory, placement drawing and authorized stage limits.	Field loading matches the analyzed arrangement before the critical operation starts.
Escalate unexplained distortion.	Located measurements, photographs, engineering assessment and disposition.	The condition receives an engineering decision; an assumed harmless origin does not close it.
Confirm the control reaches subsequent work.	Named action owner, revised procedure, completed implementation evidence and a later sample.	The later sample demonstrates the revised control operates; issuing a procedure alone is not effectiveness.

Practice application. The map connects findings to actions and acceptance evidence for comparable projects. It does not certify actual implementation or assign present regulatory duties to a named organization.

Communicate the conclusion and its limits

A defensible closing record identifies the supported initiating mechanism, the evidence that rejected competing explanations, the remaining uncertainties and the actions assigned for verification. In this case, the report supports a connection-capacity explanation; it does not establish the exact origin of earlier plate bowing. Keep that distinction explicit. Closing the causal investigation and verifying corrective-action effectiveness are separate decisions.

> **Transfer to field practice.** Preserve the evidence, test competing explanations and follow the actual load path through the connection. State what the evidence establishes, what remains uncertain and what implementation evidence is still needed. A confident label without that chain is an incomplete investigation.

MODULE 3

Technical Causal Analysis in Civil Engineering

Instructional allocation: 45 minutes

> **Module purpose.** Identify the technical mechanism, evaluate civil-specific contributors, and test competing explanations using targeted engineering analysis.

3.1 Identify the physical or functional mechanism before naming a root cause

Technical causal analysis begins by explaining how performance departed from the intended condition. For settlement, the mechanism might involve densification, consolidation, loss of support, erosion, collapse of loose fill, or movement at an interface. For cracking, the mechanism could involve restraint, movement, flexure, shear, thermal action, shrinkage, fatigue, corrosion-induced expansion, or differential support. For drainage failure, the mechanism might involve inadequate hydraulic capacity, blockage, backwater, poor grade, infiltration, or outlet instability. Naming the mechanism narrows the evidence needed to test causes.

This step protects the investigation from organizational shortcuts. If a report concludes that 'lack of communication' caused a wall to move, the reader still does not know what physical condition created the movement. If the mechanism is saturation-induced loss of soil strength, the investigation can then evaluate why water accumulated, whether drainage was designed and constructed correctly, whether

field changes affected it, whether the condition was visible, and which controls should have detected it. Organizational causes become meaningful only when connected to the technical chain.

Mechanism identification does not require certainty at the outset. The investigator may carry several mechanisms forward: bearing movement versus slope movement, restrained shrinkage versus settlement, inadequate capacity versus blockage, or construction damage versus long-term deterioration. The purpose is to organize technical testing and identify observations that would distinguish them.

3.2 Design contributors: assumptions, interfaces, detailing, and constructability

Design-related causal factors should be framed precisely. 'Design error' is usually too broad to be useful. The investigation should identify the particular assumption, calculation, criterion, interface, detail, load path, tolerance, durability feature, drainage path, redundancy provision, or constructability issue that may have influenced performance. Then the team should test whether that feature actually contributed to the observed mechanism.

Assumptions deserve a baseline comparison. What support modulus, groundwater level, traffic loading, earth pressure, drainage condition, material property, construction sequence, or boundary condition did the design use? Was the assumption reasonable based on information available at the time? Did field conditions differ materially? Was there a requirement to verify the condition before proceeding? Did new information trigger a design reassessment? These questions separate a changed field condition from an unreasonable original assumption and help avoid judging earlier design solely through hindsight.

Interfaces are a recurring source of civil failures because no single drawing tells the whole story. Structural details may depend on geotechnical support. Drainage features cross roadway, structural, landscape, or utility limits. Delegated design may depend on criteria provided by the engineer of record. Temporary works interact with permanent work. A utility conflict may prompt a field revision that changes drainage or support. The investigation should map the information exchange at the interface and determine whether the final constructed condition remained consistent with the intended performance model.

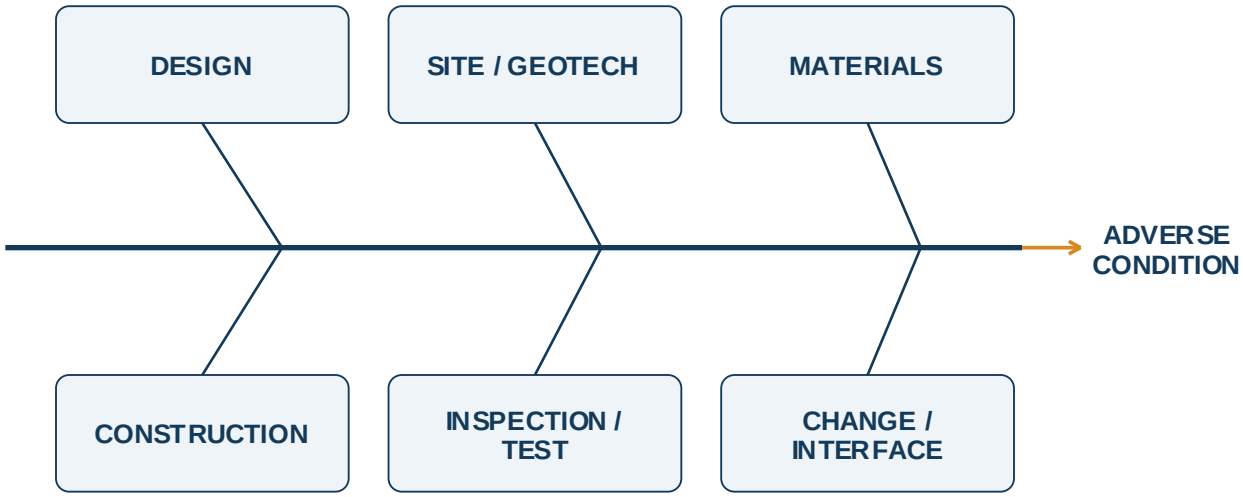


Figure 7. Civil cause-and-effect categories organize potential contributors before evidence narrows the field.

3.3 Geotechnical and site contributors require spatial thinking

Subsurface conditions are inferred from limited data. A boring, test pit, sounding, or laboratory sample describes a location and depth, not every cubic foot of soil. Failure analysis therefore requires careful spatial correlation. Plot the failed area relative to borings, fills, utility trenches, existing structures, groundwater observations, drainage paths, historic features, and construction limits. Differences that appear minor on a plan may be critical when they align with the distress pattern.

Potential site contributors include weak or variable strata, undocumented fill, organics, debris, loose zones, inadequate compaction, moisture change, groundwater rise or drawdown, leakage, scour, erosion, piping, expansive behavior, karst or voids where applicable, slope instability, bearing conditions, and interaction with adjacent excavation or loading. The investigator should focus on mechanisms that are consistent with the observed movement and project geology rather than listing every geotechnical hazard.

Field testing should be selected to answer a question. Additional borings may help characterize a broad subsurface change, while hand probes, density testing, test pits, dynamic cone penetration, piezometers, or survey monitoring may be more useful for a localized construction issue. Destructive exploration can also alter the evidence or create new instability, so the work plan should integrate safety, preservation, and the decision value of each test.

3.4 Materials and construction contributors should be tied to traceable lots and locations

Material variability is normal; the investigation needs traceability. For concrete, the relevant record may include placement location, batch tickets, sampling, curing, test age, placement conditions, finishing, temperature, reinforcement congestion, and later cores or nondestructive evaluation. For soils and aggregate, the record may include source, classification, moisture, lift thickness, compaction effort, density tests, proof-roll observations, stabilization, and weather. For asphalt, the investigation may consider mix production, temperature, density, thickness, support, placement conditions, traffic, and drainage. The purpose is to identify whether a material or process condition is mechanically connected to the observed performance.

Workmanship is a description of execution quality, not an adequate root cause by itself. If an installation dimension is outside tolerance, ask why the work was produced that way, how the condition affected performance, whether the crew had current information, whether the method could achieve the tolerance, whether the first production unit was verified, whether inspection points existed, and how the deviation escaped correction. A strong investigation can conclude that workmanship was a direct causal factor while still explaining the system conditions that allowed it.

Sequencing and temporary conditions can dominate the analysis. A permanent structure may be adequate for final loads but vulnerable during erection. Backfill may be placed before a wall or slab reaches required capacity. Waterproofing may be damaged by later work. Drainage may be temporarily blocked. Heavy equipment may load an incomplete system. The investigation should reconstruct the state of the project at the time the adverse condition developed, not assume the final configuration existed throughout construction.

3.5 Transportation and linear infrastructure failures often follow spatial patterns

Roadways, bridges, drainage systems, earthwork, utilities, retaining systems, and other linear assets provide a useful investigative advantage: the project often contains multiple similar locations that can serve as comparisons. A pavement section that fails at one station but performs elsewhere may allow the team to compare support, drainage, material lot, crew, sequence, traffic, or environmental exposure. A recurring guardrail or drainage defect may align with a particular detail, subcontractor, or construction phase. Pattern analysis can narrow the likely causal variables before expensive testing begins.

Spatial comparison should be deliberate. Define what makes a comparison location similar enough to be informative. The same material source may not be enough if subgrade conditions differ. The same drainage detail may not be enough if outlet elevation or contributing area differs. The same crew may not be enough if weather or sequence changed. A useful comparison isolates variables rather than merely identifying another location that looks similar.

Transportation investigations should also consider maintenance of traffic, staged construction, traffic loading before final acceptance, utility conflicts, access limitations, and the interaction between design disciplines and field operations. The causal chain may involve temporary conditions that disappear from the final record unless daily reports and photographs are reviewed.

HYPOTHESIS	SUPPORTING EVIDENCE	CONTRADICTING EVIDENCE	NEXT TEST / DATA
H1: Weak subgrade	Wet proof-roll area; low density	Adjacent area performs well	Compare support, drainage and compaction lots
H2: Poor drainage	Ponding, clogged outlet or saturation	Distress began before the major storm	Check grades, outlet history and moisture timeline
H3: Material variability	One test below target	Most lot results acceptable	Trace lots, sampling and the spatial distress pattern
H4: Sequence / traffic	Early heavy construction traffic	Some low-traffic zones distressed	Reconstruct traffic and staging chronology

Figure 8. An evidence matrix tests competing hypotheses using both supporting and contradicting evidence.



Illustrative field investigation: temporary excavation support and bracing are inspected as part of reconstructing the construction-stage condition. This is a contextual illustration, not a documented incident.

3.6 Quality and acceptance controls are barriers whose performance can be investigated

A test plan, hold point, design check, inspection, or acceptance review is a barrier intended to prevent or detect an unacceptable condition. Root-cause analysis asks whether the barrier existed, whether it was appropriate to the risk, whether it was performed at the right time and location, whether the result was interpreted correctly, and whether follow-up occurred. This is different from teaching the quality-management system itself; the concern here is barrier effectiveness in the specific event.

A control can fail in several ways. It may be absent. It may exist but cover the wrong location or variable. It may occur after the work is concealed. It may rely on a sample that does not represent the failed condition. It may identify a warning sign that is not escalated. It may be bypassed under schedule pressure. It may be based on outdated information. Or it may function as designed but be insufficient to detect a condition outside its intended scope. Each mode of control failure suggests a different corrective response.

The investigator should avoid assuming that more inspection is always the answer. If the causal condition is a flawed drainage detail, adding field inspection without changing the detail may not prevent

recurrence. If the issue is uncontrolled sequence, a design change may not address it. Corrective action should follow from the verified cause and barrier analysis, not from a generic preference for more paperwork or more tests.

3.7 Changes and coordination failures should be reconstructed as information pathways

Field conditions often require change. The investigation should therefore distinguish legitimate adaptation from uncontrolled change. Trace the information pathway: who identified the condition, what requirement or conflict was involved, what information was provided, who evaluated the technical impact, what response was issued, how the response was communicated, what version reached the field, and how the constructed condition was verified. This pathway can expose a failure even when each individual participant acted reasonably within an incomplete information set.

RFIs are particularly important because they may contain multiple issues under one subject. A response may clarify one dimension while leaving a related drainage or structural effect unresolved. Shop drawings may incorporate a field dimension that differs from the design basis. A value-engineering change may have downstream effects on maintenance or durability. A utility conflict may alter a grading or drainage path. The investigation should evaluate the technical consequence of the actual constructed change, not merely whether a document was approved.

Delegated design and temporary works require clarity about criteria and interfaces. The question is not simply who was responsible. It is whether the responsible party had the necessary criteria, whether the resulting design was compatible with permanent work, whether field changes were controlled, and whether required review or verification occurred.

3.8 Use calculations, testing, modeling, and specialist review to discriminate among hypotheses

Technical analysis should be proportional to the decision. A simple elevation comparison may be sufficient to demonstrate differential movement. A drainage problem may require slope checks and hydraulic calculations. A wall movement investigation may need updated soil parameters, stability analysis, survey monitoring, and water-level data. A structural distress problem may require load-path review, demand/capacity calculations, material testing, or finite-element modeling. The tool is justified when it helps distinguish plausible explanations or evaluate the adequacy of a proposed disposition.

Testing should be designed around hypotheses rather than convenience. If the question is whether a concrete placement is uniformly weak, a core plan should consider spatial coverage, structural consequence, and how cores will be interpreted. If the question is whether compaction contributed to localized settlement, tests outside the failed zone may have limited value unless they provide a controlled comparison. If drainage is suspected, dye testing, camera inspection, flow observation, or excavation may be more informative than additional material testing.

Specialists can improve the investigation when the mechanism crosses disciplines. A geotechnical engineer may be needed for subsurface movement, a materials specialist for deterioration or test interpretation, a structural engineer for load-path effects, a hydraulic engineer for flow conditions, or a survey specialist for deformation monitoring. The lead investigator should integrate specialist findings into one causal narrative and reconcile contradictions rather than compiling disconnected expert memoranda.

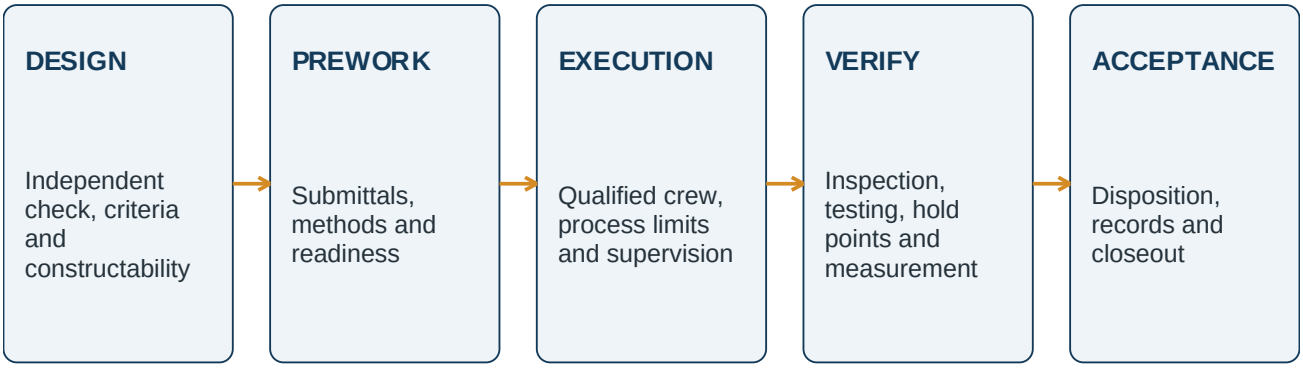


Figure 9. Barrier analysis asks where the causal condition should have been prevented, detected, or stopped.

3.9 Test competing hypotheses instead of proving the favorite one

A hypothesis is useful only if it can be challenged. For each major explanation, identify evidence that should exist if the hypothesis is true and evidence that would be difficult to explain if it is true. A drainage hypothesis may predict high moisture, a blocked path, spatial correspondence with low points, or movement after wet periods. A material hypothesis may predict correlation with a specific lot or production window. A sequence hypothesis may predict distress at locations loaded before a milestone. A design hypothesis may predict similar behavior wherever the same detail and conditions occur.

Contradicting evidence is especially valuable. If the same suspect material performs well in comparable locations, the team must explain why. If a wall moved before groundwater rose, water may still contribute but cannot explain initiation. If density tests are acceptable, determine whether they represent the failed zone rather than dismissing the geotechnical hypothesis. The goal is not to accumulate points for one theory; it is to find the explanation that best accounts for the entire evidence set.

Complex civil failures often have multiple necessary contributors. Saturated support may be required, but the condition may only become damaging under early construction traffic. An inadequate detail may create vulnerability, while a missed inspection allows the condition to persist. Root-cause analysis should preserve this interaction rather than forcing a single-cause label.

3.10 Applied technical workshop: retaining wall movement

Assume survey monitoring identifies outward movement of a mechanically stabilized or reinforced-soil retaining system after substantial backfill placement. The movement is greatest near one end and appears to accelerate after rainfall. The initial technical hypotheses could include foundation settlement, global or local stability, inadequate reinforcement or connection behavior, backfill properties, construction sequence, compaction-induced load, groundwater, blocked drainage, changed geometry, or an interaction among several conditions. The team should map movement magnitude and rate, review baseline survey control, examine design assumptions, compare actual backfill and geometry, review drainage and groundwater evidence, reconstruct sequence, and identify any field changes.

The investigation should avoid treating post-rainfall acceleration as proof that drainage is the root cause. If movement began earlier, water may be an amplifier rather than the initiating condition. If similar wall segments with the same drainage perform well, compare foundation and sequence. If the movement is concentrated near a utility or grading transition, evaluate that interface. Calculations should use field-informed conditions rather than simply rerunning the original model. The final causal conclusion should explain the movement mechanism, the contributing conditions, and why project controls did not prevent or detect the condition sooner.

Module 3 - Key points

- Identify the technical mechanism before assigning organizational root causes.
- Test design assumptions against actual site and construction conditions.
- Use spatial patterns and comparison locations to isolate causal variables.

- Treat inspection, testing, review, and acceptance as barriers whose effectiveness can be evaluated.
- Use calculations and tests to discriminate among hypotheses, not merely to produce more data.

MODULE 4

Root-Cause Tools Adapted to Civil Projects

Instructional allocation: 40 minutes

> **Module purpose.** Select and apply root-cause tools that clarify sequence, differences, controls, hypotheses, and causal relationships without oversimplifying the event.

4.1 Choose the tool after understanding the event

Root-cause tools are ways to structure reasoning; they are not substitutes for engineering analysis. A simple, well-documented field defect may need only a chronology and a focused five-whys discussion. A progressive infrastructure failure may require a cause-and-effect map, change analysis, technical calculations, and an evidence matrix. A high-consequence event with multiple barriers may benefit from fault-tree or barrier analysis. The investigator should select the simplest combination that can represent the complexity of the event and make the reasoning transparent.

Tool selection should also reflect evidence quality. A detailed fault tree can create an appearance of rigor even when its branches are based on assumptions. Conversely, a short chronology can be highly persuasive when the field facts and sequence directly explain the event. The goal is traceable reasoning: a reviewer should be able to see which facts support the proposed causal chain, which alternatives were considered, and where professional judgment enters.

Several tools can be used together without duplicating work. Chronology organizes sequence. Fishbone analysis organizes categories of potential contributors. Change analysis highlights differences between successful and failed conditions. Barrier analysis identifies controls that should have prevented or detected the event. An evidence matrix tests hypotheses. The final causal statement synthesizes the results.

4.2 Chronology and event-and-causal-factor analysis

Chronology is often the highest-value root-cause tool in construction because sequence changes conditions. Create a time-ordered list of significant technical events and decisions. Include both physical events and information events: excavation, material placement, testing, design response, field change, rainfall, loading, distress detection, inspection, repair, and monitoring. The timeline should include only events that help explain the condition or the control path; unrelated project history adds noise.

Event-and-causal-factor analysis adds a second layer by linking conditions to events. For example: prolonged rain occurs; temporary drainage outlet is obstructed; support moisture rises; heavy equipment traffic continues; rutting is first observed; the condition is graded over; final surface is placed; distress reappears. Each box can be supported by a record or identified as an inference. This approach exposes the difference between the initiating event, enabling conditions, and missed opportunities for intervention.

The timeline can also reveal impossible explanations. If a suspected change occurred after the distress was documented, it cannot be the initiating cause. If a test result was received after the work was concealed, the question may shift from whether testing occurred to whether the response system could act in time. Chronology is therefore both an explanatory and a falsification tool.

4.3 Five whys: useful when the chain is focused, weak when the system is complex

Five-whys questioning is simple: ask why an observed problem occurred, then continue asking why each causal condition existed until the analysis reaches a controllable underlying factor. The method is useful for focused process failures. Why was the anchor bolt installed at the wrong elevation? Because the crew used an incorrect setting dimension. Why? Because the layout sheet reflected an earlier

revision. Why? Because the revised detail was issued but the field-controlled set was not updated. This chain points toward a document-control failure that can be corrected.

The method becomes weak when the event has branching causes. Pavement distress may require both wet support and loading. A wall movement event may involve site variability, drainage, sequence, and monitoring. Asking one linear series of whys can force the investigator to choose a single branch and ignore interacting conditions. Five whys can also drift into vague statements such as 'lack of training' because the team stops asking technical questions.

Use five whys as a probe, not as a mandatory five-step ritual. Stop when the cause is sufficiently specific, evidence-supported, and actionable. Continue when the answer is merely a label. 'Human error' is not the end of the analysis if the investigation has not explained the information, tools, conditions, and controls that shaped the action.

VARIABLE	COMPARISON CONDITION	DISTRESSED CONDITION
Location	Station 120+00 performs	Station 124+50 is distressed
Material	Source A	Source B after supplier change
Weather	Dry placement	Placement after prolonged rainfall
Sequence	Base protected before traffic	Construction traffic before final course
Drainage	Outlet open	Temporary outlet obstructed
Crew / method	Crew 1 and approved sequence	Crew 2 and altered sequence

Figure 10. Change analysis compares successful and failed conditions to isolate variables that deserve focused testing.

4.4 Cause-and-effect analysis: organize hypotheses before narrowing

Cause-and-effect or fishbone analysis is useful early in a complex civil investigation because it forces the team to look beyond the dominant theory. Categories can be adapted to the project: design, site/geotechnical conditions, materials, construction, equipment/resources, inspection/testing, change/coordination, environment, and operations. The team lists plausible contributors under each branch and then marks which items have evidence, which are contradicted, and which require follow-up.

The fishbone is an inventory, not a conclusion. A branch with many ideas is not more likely than a branch with one strong cause. The tool should therefore transition quickly into evidence testing. For example, 'high groundwater' under site conditions may become a specific question: what was the water level when movement began, how does it compare with design assumptions, and what evidence exists at the failed location? 'Poor communication' under coordination should become a traceable information-path question.

The method is particularly useful in multidisciplinary review meetings because participants can see how their discipline fits into the system. The investigator should prevent the session from turning into brainstorming without closure by assigning evidence owners and due dates to the highest-value questions.

4.5 Change analysis: compare what was different

Change analysis asks what differed between the failed condition and a successful or baseline condition. The comparison may involve location, material source, crew, equipment, sequence, weather, design revision, drainage status, loading, inspection coverage, or time. It is powerful because many civil projects contain repeated elements that allow controlled comparisons.

The method should be explicit about what did not change. Suppose two pavement segments used the same asphalt mixture, but only one distressed. That fact reduces the likelihood that asphalt mixture

alone explains the pattern, though it does not eliminate interactions. If both segments share subgrade but only one experienced early construction traffic, traffic becomes a stronger variable. If a wall detail performs throughout the project except near one utility crossing, the interface deserves attention.

Change analysis can also compare before and after a modification. Did distress accelerate after dewatering stopped? Did the defect rate change after a crew or supplier change? Did monitoring stabilize after drainage was restored? These observations can strengthen causal inference, especially when the mechanism is consistent with the change.



Illustrative field investigation: retaining-wall displacement is measured and documented so competing causal explanations can be tested against field geometry. This is a contextual illustration, not a documented incident.

4.6 Fault-tree logic: decompose the top event

Fault-tree analysis starts with a defined top event and asks what combinations of conditions could produce it. In civil work, the method is most useful when the event has clear logical pathways. A top event such as 'loss of excavation stability' might be decomposed into inadequate support capacity, excessive demand, loss of restraint, groundwater effects, or a combination. Each branch can be decomposed further into design, installation, sequence, environmental, or control factors.

The value is conceptual clarity, not necessarily probability calculation. The tree shows whether several conditions must occur together and helps the team identify evidence needed to close branches. It also reveals when a proposed root cause is too remote. 'Schedule pressure' may influence a decision but does not directly explain instability unless the tree shows the action it changed and the technical consequence of that action.

Fault-tree logic should be kept readable. Deep trees built from uncertain assumptions can obscure rather than clarify. For most continuing-education examples, a few levels are sufficient to show how technical and control conditions combine.

4.7 Barrier and control analysis: where should the problem have been stopped?

Barrier analysis shifts the question from 'who made the mistake?' to 'what control should have prevented, detected, or limited the condition?' Civil projects use many barriers: design criteria, independent checks, constructability review, submittal approval, temporary-works design, preconstruction meetings, hold points, inspection, testing, survey verification, alarms, monitoring thresholds, acceptance reviews, and maintenance inspections. The investigator should identify the barriers relevant to the specific causal chain.

Then evaluate each barrier. Was it present? Was it technically capable of detecting the condition? Was it located at the right point in the sequence? Did qualified personnel perform it? Was the result documented? Was the information communicated to someone with authority to act? Did the project respond? A barrier that identifies a problem but has no timely escalation path is only partially effective.

Barrier analysis is one of the strongest bridges between root cause and corrective action. If the investigation shows that a critical temporary drainage condition was not included in prework and follow-up inspections, the corrective action can target that control. If the barrier existed but the underlying design criterion was inadequate, adding inspections would not address the real cause.

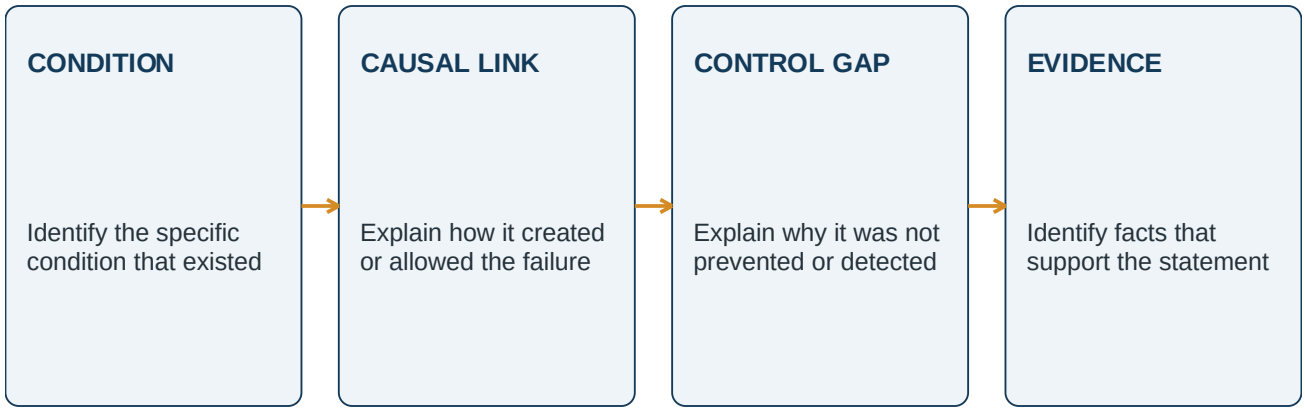


Figure 11. A defensible causal statement links a specific condition, causal relationship, failed control, and evidence.

4.8 Evidence matrices make competing explanations inspectable

An evidence matrix lists each major hypothesis and separates supporting evidence, contradicting evidence, unresolved questions, and the next test or data source. This structure is particularly useful when different stakeholders favor different explanations. The matrix forces each theory to be evaluated by the same standard instead of by persuasion.

The investigator should distinguish absence of evidence from evidence of absence. No documented ponding does not prove the site stayed dry if no one was observing during the relevant period. Conversely, repeated photographs showing open drainage paths during the period of movement are meaningful contradicting evidence for a blockage hypothesis. The matrix should also identify evidence quality: direct measurement, contemporaneous record, later recollection, or engineering inference.

As the investigation progresses, hypotheses may be merged or reframed. A material hypothesis and drainage hypothesis may combine into an interaction: material was marginal but performed acceptably when dry, while prolonged saturation reduced support enough for traffic to produce distress. The matrix helps preserve the evidence for each component of that combined explanation.

4.9 Write causal statements that explain the relationship

A root-cause statement should identify the condition, explain how it contributed to the event, identify the failed control when relevant, and point to supporting evidence. 'Poor workmanship' does not satisfy this test. A stronger statement might be: 'Backfill adjacent to the utility crossing was placed in lifts substantially thicker than the approved procedure, producing localized low-density zones that later densified under traffic. The condition escaped detection because density tests were performed outside the crossing influence zone and the first-lift verification hold point was not applied after the utility subcontractor changed sequence.' This statement can be challenged and it points directly to corrective actions.

Causal statements should avoid moral language unless intent is genuinely relevant. Terms such as careless, negligent, or incompetent are legal or personnel conclusions that usually add little engineering value and may exceed the purpose of an internal technical investigation. Describe the action, information, condition, and effect. If a required procedure was not followed, state what requirement applied, what occurred, and how the deviation influenced the technical outcome.

The statement should also respect uncertainty. If evidence supports a contribution but not exclusivity, use language such as contributed to, increased susceptibility, allowed, or was consistent with. Reserve caused by for relationships the evidence truly supports.

4.10 Select the minimum sufficient root-cause package

For a moderate nonconformance, the minimum sufficient package may be a chronology, a short change analysis, and one causal statement tied to corrective action. For a recurring field defect, add a fishbone and pattern comparison. For a complex infrastructure failure, add barrier analysis, an evidence matrix, and technical calculations. For a high-consequence event, independent review and more formal evidence control may be appropriate. The process should scale with consequence, complexity, recurrence, and uncertainty.

Over-analysis has its own risks. A large team can generate so many diagrams and categories that the decisive evidence becomes hard to see. The investigation lead should continually ask which unresolved question could change the decision. If a new analysis will not affect cause, disposition, or corrective action, it may not be necessary. Technical completeness does not mean collecting every possible fact; it means having enough reliable evidence and reasoning to support the engineering decision.

Module 4 - Key points

- Select root-cause tools based on event complexity and evidence quality.
- Use chronology to test sequence and eliminate explanations that do not fit time.
- Use five whys for focused chains, not as a substitute for multi-cause analysis.
- Use barrier analysis to connect verified causes to effective corrective controls.
- Write causal statements that explain the technical relationship and preserve uncertainty.

MODULE 5

Nonconforming Work, Corrective Action & Recurrence Prevention

Instructional allocation: 40 minutes

> **Module purpose.** Separate repair from corrective action, make defensible engineering dispositions, and verify that recurrence risk has actually been reduced.

5.1 Separate containment, correction, disposition, and corrective action

A common failure-analysis mistake is to treat the physical repair as the corrective action. The repair may restore the asset, but it does not necessarily prevent recurrence. Containment is the immediate action taken to protect people, limit extent, preserve evidence, or stop additional nonconforming work. Correction fixes the specific observed condition. Engineering disposition determines what technical response is acceptable for the nonconforming work. Corrective action addresses the verified causal conditions and failed controls. Effectiveness verification determines whether the corrective action actually changed performance.

These decisions can occur on different timelines. A damaged barrier may need immediate temporary repair before the investigation is complete. A concrete placement may require structural evaluation before final disposition. A recurring compaction issue may justify a process hold while the team investigates. The project should document which action is temporary, which is final, who has authority to approve it, and what evidence is required before work resumes.

Clear terminology improves accountability. If a team closes a root-cause item because the cracked slab was repaired, the causal process may remain unchanged. If the investigation concludes that the defect resulted from sequence and protection of completed work, corrective action may involve work planning, access control, and verification in addition to the repair detail.

5.2 Characterize the nonconformance before deciding what to do

Engineering disposition requires a defined condition. Record the location, extent, dimensions, material, requirement not met, associated test results, construction history, and any immediate risk. Determine whether the condition is isolated or potentially systemic. A single low test result may represent one lot, multiple placements, or a sampling anomaly. A geometric deviation may be local or repeated because the same layout control was used. The investigation should establish the extent of condition before the project assumes the problem is limited.

The applicable requirement should be cited precisely in the project record: drawing detail, specification section, approved submittal, tolerance, agency requirement, design criterion, or other controlling source. Avoid generic statements such as 'not built per plan' if several requirements could be involved. The engineering significance depends on what the deviation changes: capacity, serviceability, durability, drainage, clearance, fit, constructability, maintenance, appearance, or future work.

Characterization may require additional testing or exposure. The work plan should avoid testing for testing's sake. Define what decision each test supports. A core may help determine in-place concrete properties. Survey may quantify geometry. Probe or excavation may define extent. Drainage testing may establish function. Monitoring may show whether movement is active. The engineering review should identify the minimum data needed to support a disposition with appropriate confidence.

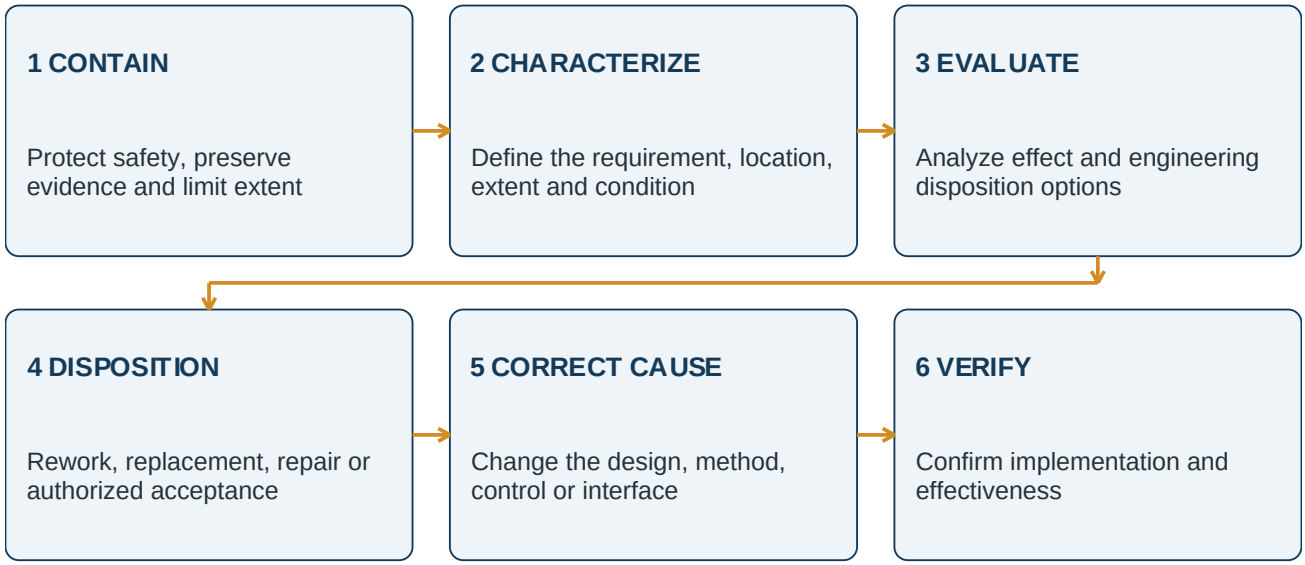


Figure 12. Containment, characterization, evaluation, disposition, corrective action, and effectiveness verification are distinct stages.

5.3 Disposition options carry different technical and contractual implications

Common technical dispositions include remove and replace, rework, engineered repair, authorized acceptance or use-as-is where permitted, and monitored acceptance subject to defined limits. The correct option depends on applicable project requirements, authority, consequence, and the engineering evaluation. A field team should not convert a nonconformance into an informal acceptance simply because removal is expensive or schedule-sensitive.

Remove and replace is often appropriate when conformance can be restored without creating greater risk or when the deviation cannot be technically justified. Rework modifies the existing work to bring it into the required condition. An engineered repair accepts that original conformance cannot be restored exactly but designs a specific technical solution that achieves required performance. Authorized acceptance or use-as-is should be reserved for circumstances where the controlling contract and authority permit it and where engineering evaluation shows the deviation does not compromise required performance.

Monitoring can be part of a disposition when the performance can be bounded by measurable criteria and there is a defined escalation path. Monitoring is not a substitute for engineering analysis. The plan

should identify what will be measured, baseline, frequency, alert and action thresholds, responsible party, duration, data-review method, and what happens if the threshold is exceeded.

5.4 Evaluate the repair as a new engineering condition

A repair changes the system. The engineer should evaluate not only whether the repair addresses the original defect but also whether it introduces new load paths, stiffness changes, drainage paths, stress concentrations, access limitations, durability concerns, construction sequence risks, or future inspection challenges. A patch that restores surface appearance may trap water. Added anchors may alter edge distances. A rigid repair may create a stiffness discontinuity. Excavation to repair a utility may destabilize adjacent support. The repair itself deserves a focused constructability and risk review.

Repair design should define acceptance evidence. What inspection is required before concealment? What material properties must be verified? Is survey required? Are proof loads, leak tests, density tests, weld inspection, curing records, or photographs needed? If the failure investigation identified weak verification as a contributing cause, the repair plan should not repeat the same control weakness.

Temporary support and sequence are often more critical during repair than in the final condition. The field plan should identify load restrictions, excavation limits, bracing, traffic staging, dewatering, protection, and hold points as applicable. The investigation record should connect repair assumptions to actual field execution so that the final disposition can be closed on evidence rather than intent.

DISPOSITION	TECHNICAL BASIS
Remove / replace	Condition cannot meet the requirement or its risk cannot be justified.
Rework	Work can be brought into conformance using an approved method.
Engineered repair	A specific analysis and detail restore the required performance.
Authorized acceptance	Use as-is only where permitted and technically justified.
Monitor	Define criteria, instrumentation, limits and an escalation path.

Figure 13. Engineering disposition must match the technical condition and the authority defined by the project requirements.



Illustrative field investigation: damaged reinforced concrete is examined closely before repair so the extent, mechanism, and acceptance requirements can be defined. This is a contextual illustration, not a documented incident.

5.5 Corrective actions should target verified causes and failed barriers

Corrective action is strongest when it changes the causal condition itself. If an inadequate drainage detail created saturation, redesigning the drainage path is stronger than reminding inspectors to watch for ponding. If uncontrolled sequence caused overloading, a revised work plan and hold point may be stronger than a general training session. If testing did not represent a critical transition zone, the sampling plan should be changed. If an RFI pathway allowed a field clarification to bypass the engineer responsible for an affected discipline, the change-control interface should be redesigned.

A useful hierarchy starts with elimination or redesign, then engineering controls, verification controls, process and communication controls, and finally training or reminders. Lower-level actions are not inherently wrong; they are weak when used as the default response without evidence that knowledge or attention was the causal problem. Training is appropriate when the investigation shows a skill or knowledge gap. It is not an adequate response to a design condition, inaccessible inspection point, impossible tolerance, or contradictory instruction.

Corrective action should also address the extent of condition. If the same process, detail, supplier, crew, or control exists elsewhere, the team should determine whether other locations require review. A root cause that can exist on multiple projects may justify an organizational action in addition to the project-specific fix.

ORDER	ACTION	BASIS
1	Eliminate / redesign	Remove the causal condition; change geometry, detail, drainage, support or interface.
2	Engineering control	Add physical control, redundancy, protection, stabilization or monitoring.
3	Verification control	Add a hold point, inspection, testing, survey, acceptance criterion or independent check.
4	Process / communication	Improve RFI, change control, submittals, sequencing, coordination or work planning.
5	Training / reminder	Use when evidence shows knowledge or skill was causal; do not use by default.

Figure 14. Corrective actions are strongest when they eliminate the causal condition or strengthen engineering and verification controls.

5.6 Define ownership, due dates, completion evidence, and effectiveness criteria

An action item is not complete because someone changed a procedure. The corrective-action record should identify the owner, required deliverable, due date, implementation location, completion evidence, and effectiveness measure. For example, 'revise the inspection plan' is incomplete. A better action is: 'Before the next retaining-wall lift exceeds Elevation X, the contractor quality manager will revise the inspection and test plan to add a documented drainage-path verification hold point at each outlet zone; the CEI lead will verify implementation on the first three locations and report results.' The second version can be audited.

Effectiveness criteria should be defined when the action is assigned, not after implementation. Criteria may include no recurrence over a defined production quantity, passing verification results, stable monitoring data, elimination of repeat NCRs, successful first-article inspection, improved traceability, or documented completion of a new review step on a sample of projects. The metric should be connected to the failure mechanism and control path.

Schedule is part of the engineering decision. Some actions must be complete before work resumes; others can be implemented over time. The team should identify interim controls when the permanent corrective action cannot be implemented immediately.

5.7 Verify effectiveness with evidence, not optimism

Effectiveness verification asks whether the corrective action changed the outcome the investigation intended to change. If drainage was redesigned, verify that water is conveyed under representative conditions and that related distress does not recur. If a new inspection hold point was added, verify that it actually occurs before concealment and that findings are acted upon. If a new survey check is required, review the data and confirm deviations are detected before downstream work proceeds.

Verification should consider leading and lagging evidence. Leading evidence confirms that the control is being implemented: completed hold-point records, survey checks, documented design reviews, or updated work plans. Lagging evidence confirms performance: reduced defect recurrence, stable movement, acceptable testing, or successful service over time. A control can be implemented perfectly yet still be ineffective if it does not address the true cause.

When recurrence occurs, reopen the causal logic instead of simply strengthening the same action. The original root cause may have been incomplete, the action may have been poorly implemented, or a second pathway may exist. Recurrence is evidence. Treat it with the same discipline as the original event.

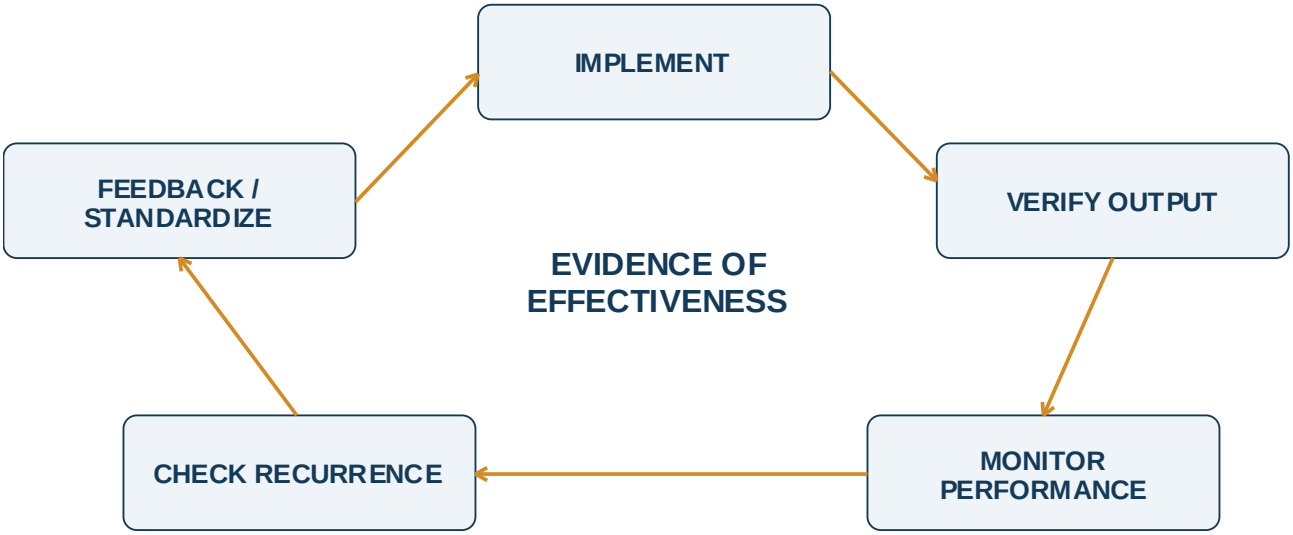


Figure 15. Corrective action remains open until evidence shows sustained effectiveness.

5.8 Turn lessons learned into specific engineering feedback

Lessons learned are most valuable when they change future engineering work. A generic lesson such as 'communicate better' is difficult to implement. A specific lesson might change a design checklist to require explicit drainage verification at wall transitions, add a constructability review for temporary access loading, require a geotechnical hold point after undercut, revise a standard detail, add a field survey check before a pour, or identify a recurring utility-interface risk in preconstruction planning.

Feedback should reach the part of the system that can use it. A design issue belongs in design guidance, standard details, criteria, or review checklists. A field-sequence issue belongs in work planning and readiness controls. A testing representativeness issue belongs in the inspection and test plan. A recurring material issue may belong in source qualification or procurement controls. A maintenance-related cause belongs in operations guidance and asset inspection.

Organizations should also preserve what worked. Investigations often identify effective barriers that limited consequence: an inspector stopped work, monitoring detected movement early, a hold point prevented concealment, or an RFI exposed a coordination issue. Reinforcing successful controls is part of recurrence prevention.

5.9 Applied disposition workshop: concrete or structural-material nonconformance

Assume a structural concrete placement has cylinder results below the specified acceptance threshold, while visual inspection shows no obvious distress. The investigation and disposition should remain separate but coordinated. First, characterize the placement: exact elements, batch and sampling records, curing, test age, placement conditions, consolidation, finishing, and whether other test results represent the same concrete. Determine the governing acceptance procedure and what additional evaluation is authorized. If cores or other testing are used, define locations and how results will be interpreted.

The root-cause analysis should not assume that low test results prove low in-place strength or that an acceptable core automatically proves the process was controlled. Potential causes may include actual material strength, sampling, specimen fabrication, curing, testing, batch variability, water addition, placement conditions, or record traceability. The engineering disposition may ultimately accept, repair, strengthen, or replace the work depending on the applicable criteria and evaluation. Corrective action should address the verified cause of the nonconformance or the control failure that created uncertainty. This distinction is essential: the final structure can be technically acceptable while the process still requires corrective action to prevent recurrence.

Module 5 - Key points

- Do not confuse repair with corrective action.
- Characterize the extent and governing requirement before engineering disposition.
- Evaluate repair effects, sequence, constructability, and acceptance evidence as a new engineering condition.
- Assign corrective actions to verified causes and failed barriers, with measurable completion evidence.
- Close corrective action only after effectiveness is verified.

MODULE 6

Applied Civil Case Scenarios, Lessons Learned & Professional Documentation

Instructional allocation: 35 minutes

> **Module purpose.** Integrate the method through civil case scenarios and communicate findings, uncertainty, corrective actions, and lessons learned in a traceable report.

6.1 Scenario A - Premature roadway and pavement distress

A recently rehabilitated roadway develops localized rutting, cracking, and edge deformation near a drainage low point. The visible distress is concentrated in one 200-foot segment. The first task is to define the pattern and performance departure: lane, station, wheel path, depth of rutting, crack type, shoulder condition, drainage geometry, and progression over time. Immediate actions may include traffic control, temporary drainage, or load restrictions depending on severity.

Evidence should be organized to test several interacting hypotheses: saturated support from drainage deficiency; inadequate compaction or variable subgrade; base material variability; asphalt thickness or density; early heavy construction traffic; utility trench influence; or an acceptance-control gap. Compare the failed segment with nearby successful segments. Trace material lots and density tests. Review rainfall and outlet condition. Reconstruct sequence and when traffic was permitted. Survey grades and drainage. The strongest conclusion may involve interaction: drainage allowed prolonged saturation, a transition zone had marginal support, and heavy traffic produced deformation before the final surface course.

Corrective action should match the verified chain. Reconstructing the pavement without correcting drainage or transition support can recreate the failure. Conversely, adding drainage alone may not restore already damaged material. The final package may require removal, support correction, drainage modification, pavement reconstruction, revised inspection/test coverage at transition zones, and an effectiveness review after a wet season.

6.2 Scenario B - Retaining wall or foundation movement

A retaining system or shallow foundation shows movement after backfill and site grading. Survey indicates that movement is concentrated near one end and has not stabilized. The investigation should preserve baseline and current survey control, map movement, document cracks or rotation, and capture drainage and groundwater conditions before repair. Review geotechnical data, foundation preparation, backfill material, compaction, wall geometry, reinforcement or support details, drainage, utilities, sequence, and adjacent loading.

Competing mechanisms may include foundation settlement, global instability, local bearing, connection or reinforcement behavior, excessive lateral loading, inadequate drainage, changed geometry, or construction-induced effects. Rainfall correlation may be important, but the team should determine whether movement began earlier. If monitoring shows acceleration with water levels, the evidence supports a hydraulic contribution. If movement aligns with a utility trench or foundation transition, the site

model may need refinement. Updated analysis should use conditions supported by field evidence rather than simply repeat original assumptions.

Disposition may require temporary stabilization, unloading, drainage restoration, ground improvement, structural repair, reconstruction, or monitored use depending on the mechanism and consequence. Corrective action should address why the causal condition existed and why monitoring, inspection, or design interfaces did not identify it sooner.

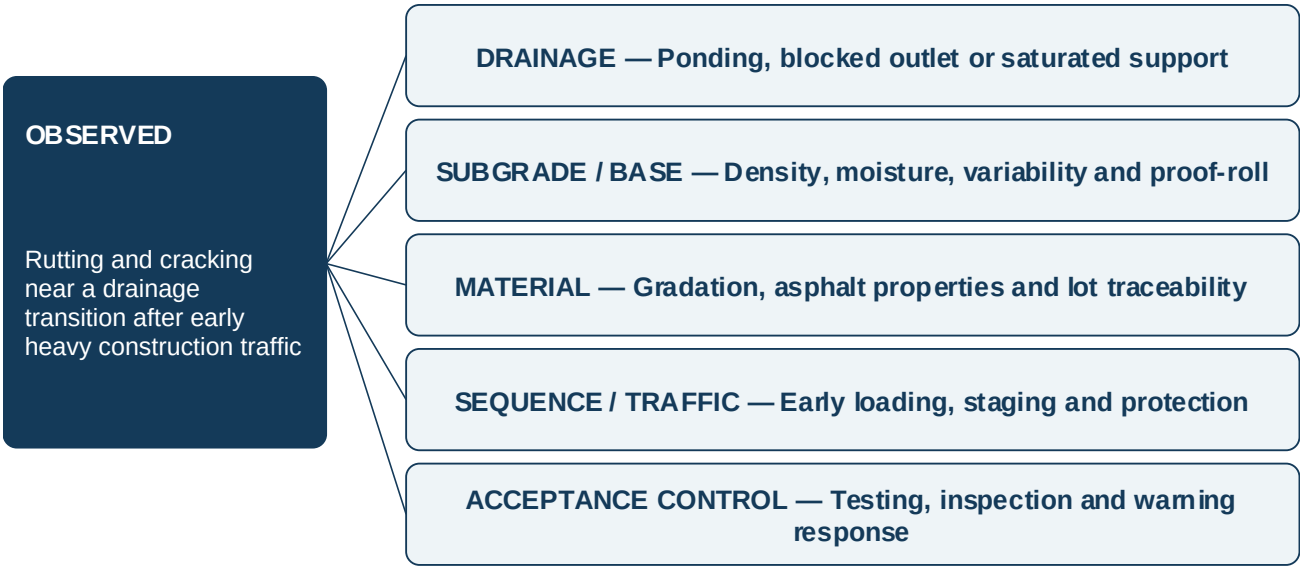


Figure 16. Pavement distress should trigger competing hypotheses involving drainage, support, materials, loading/sequence, and acceptance controls.

6.3 Scenario C - Concrete or material nonconformance

A series of material test results indicate potential nonconformance, but the affected work is already in place. The investigation begins with traceability: which lots, placements, stations, or structural elements are represented; whether sampling and testing were performed correctly; whether retests exist; and what construction records show. Extent-of-condition analysis is critical because a single test may represent a limited lot or may be a signal of a wider production issue.

The technical mechanism depends on the material and observed performance. For concrete, strength, durability, placement, curing, and structural demand may matter. For earthwork, density, moisture, material type, lift thickness, support, and later saturation may matter. For asphalt, mixture, density, thickness, support, temperature, and drainage can interact. The investigation should avoid turning the acceptance test itself into the cause. Tests are evidence about a condition; the causal analysis explains why the condition occurred and whether it is connected to the observed performance.

A technically acceptable final disposition does not erase the need to investigate the process when the control system failed. If supplemental evaluation shows the work can remain, the team should still address sampling, production, communication, or response weaknesses that created the nonconformance or uncertainty.

6.4 Scenario D - Temporary works and construction sequencing problem

During staged construction, unexpected movement occurs in temporary shoring or an incomplete structural system. The investigation must reconstruct the exact configuration at the time of movement: installed members, braces, connections, excavation depth, backfill, concrete strength, equipment location, temporary loads, weather, and sequence. Permanent design drawings may not describe this condition. Temporary-works calculations, erection plans, delegated-design documents, field sketches, and daily reports become primary evidence.

Potential causal paths include inadequate temporary capacity, missing or altered bracing, sequence change, field modification, load beyond the assumed limit, groundwater or excavation effects, incomplete connection, communication failure between designer and contractor, or insufficient verification before advancing the stage. Barrier analysis is especially useful: what design review, prework check, hold point, survey, or field verification should have prevented the configuration from reaching an unsafe state?

Corrective action should address both the immediate temporary condition and future stages. A repair or added brace may stabilize the current stage, while revised sequencing, load limits, field-change controls, survey thresholds, or independent review may be necessary to prevent recurrence.

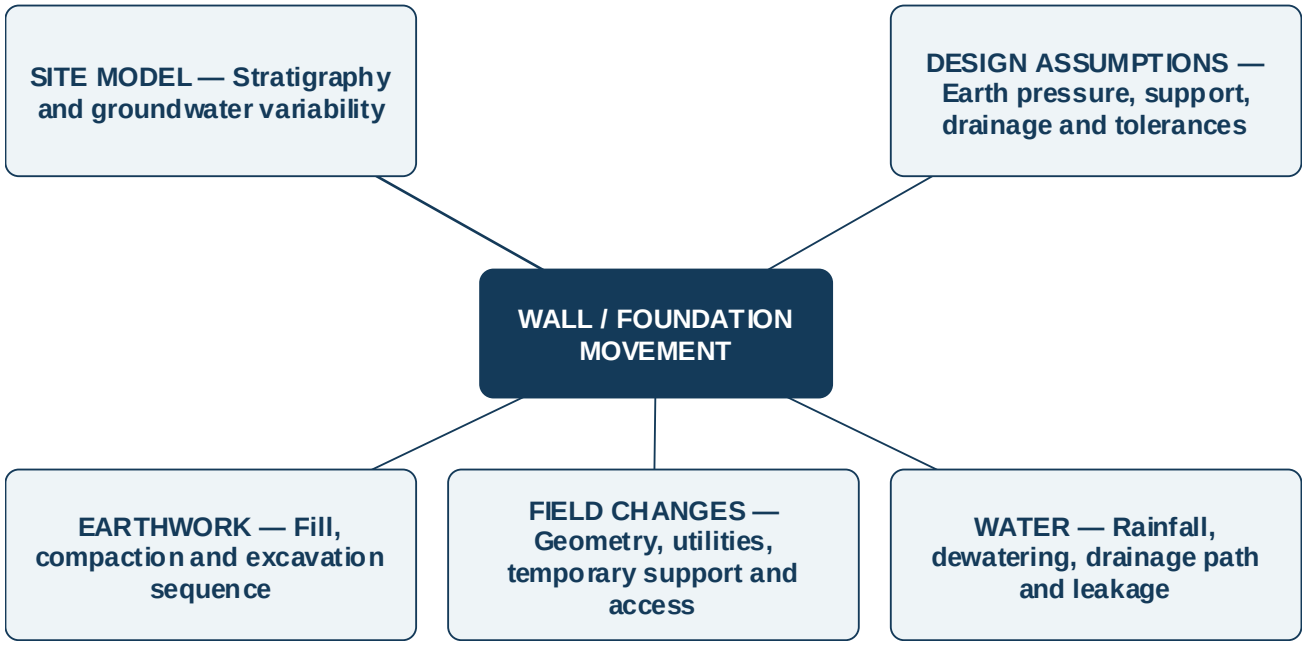


Figure 17. Retaining-wall or foundation movement often requires integrated site, design, earthwork, water, and field-change analysis.

6.5 Scenario E - Utility and multidisciplinary coordination failure

A roadway drainage line conflicts with an existing utility, prompting a field adjustment. Months later, the area experiences settlement and drainage complaints. The investigation should trace the information path from utility location through conflict identification, RFI or field direction, revised geometry, construction, inspection, and as-built documentation. The technical question is not merely whether coordination was poor, but how the revised configuration changed support, drainage, access, or construction sequence.

Review whether the utility was field-verified, which disciplines evaluated the change, whether the revised grade maintained hydraulic function, how trench backfill was restored, whether pavement support was re-established, and whether the final condition was surveyed. A coordination failure becomes causal only when linked to a physical mechanism. The event may involve both a drainage-path change and a poorly compacted trench transition, for example.

Corrective action may involve a project-specific repair and a broader interface control: defined multidisciplinary review for utility-related geometry changes, survey verification before final surfacing, clearer as-built requirements, or a hold point for trench restoration at critical pavement locations.

6.6 Build the final report so the reasoning is traceable

An investigation report should allow a technically competent reviewer to follow the reasoning from the problem statement to the corrective action. A practical structure includes scope and decision purpose; background and applicable requirements; evidence reviewed; chronology; field observations; analyses and tests; findings; assumptions and limitations; causal analysis; conclusions; disposition or

recommendations; corrective actions; and effectiveness verification. Appendices can hold detailed logs, calculations, photographs, test data, and document indexes so the main narrative remains readable.

Every major conclusion should have a visible evidence path. If the report concludes that saturation contributed to settlement, identify the field observations, moisture or groundwater data, drainage condition, timing, and mechanical rationale. If the report concludes that a verification control failed, identify the required control, what occurred, and how the gap affected the outcome. This traceability is more valuable than adding technical jargon.

Separate fact, professional judgment, assumption, and unresolved uncertainty. A reader should know whether a statement comes from measurement, a contemporaneous record, calculation, interview, later reconstruction, or engineering inference. This discipline protects both the technical quality and credibility of the report.

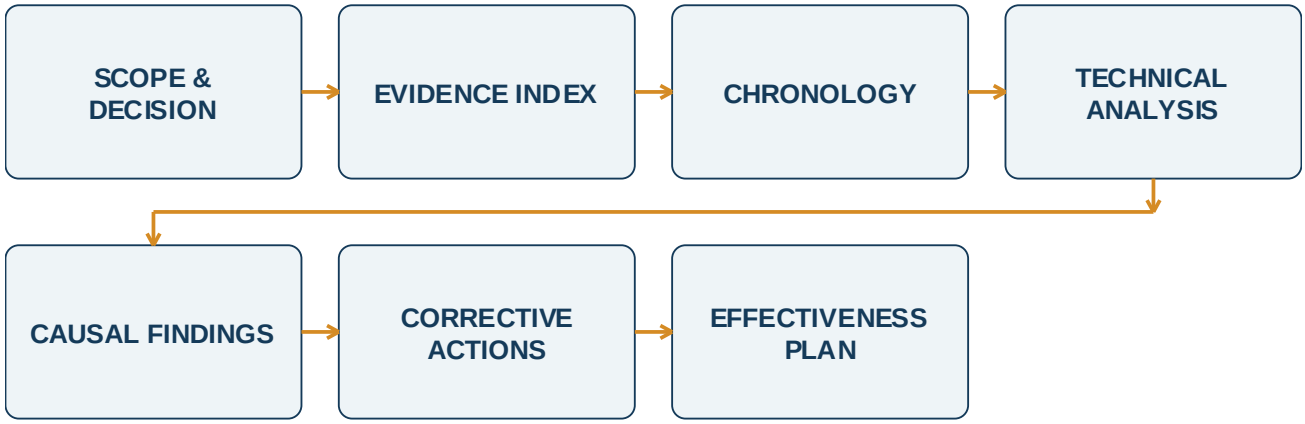


Figure 18. The final investigation record should preserve traceability from scope and evidence through causal findings and effectiveness.

6.7 Communicate certainty proportionally

Engineering reports often fail at the language level even when the technical work is sound. Words such as definitely, proved, impossible, and sole cause should be used only when the evidence supports that degree of certainty. Civil systems are variable and evidence can be incomplete. A conclusion may be strongly supported without being exclusive. Terms such as primary contributor, contributing condition, consistent with, likely, or not supported by available evidence can more accurately express the reasoning.

Uncertainty should not become an excuse for indecision. The engineer can make a defensible decision while acknowledging limits. For example, available evidence may not distinguish between two specific sources of saturation, yet both are addressed by a drainage repair and monitoring plan. Or a wall movement investigation may support continued use under defined monitoring thresholds even while long-term cause evaluation continues. The report should connect uncertainty to the decision and risk controls.

Avoid attributing motive or fault unless the investigation has a defined need and evidentiary basis for doing so. Technical reports are strongest when they describe actions, conditions, requirements, and consequences. Personnel, contractual, insurance, and legal determinations can be made by the appropriate parties using the technical record.

6.8 Convert the investigation into institutional learning

The final question is what the organization should do differently because of the investigation. The answer should be specific enough to change future work. A pavement failure may add a drainage-transition verification step. A wall movement event may change geotechnical hold points or monitoring triggers. A temporary-works incident may require better criteria transfer and field-change control. A

concrete nonconformance may change test traceability or first-placement review. A utility conflict may require multidisciplinary signoff for geometry changes.

Lessons learned should also capture decision signals that were available before failure. Was there an early observation, test trend, RFI, inspection note, or monitoring change that could have triggered intervention? The goal is not to criticize past participants with hindsight. It is to improve future recognition thresholds and escalation paths.

The best failure investigation therefore becomes a design and project-delivery input. It strengthens assumptions, details, specifications, work planning, inspection, testing, change management, maintenance, and professional judgment. That is the practical value of root-cause analysis: not merely explaining yesterday's event, but improving tomorrow's engineering.

Module 6 - Key points

- Use case scenarios to integrate mechanism, evidence, causal reasoning, disposition, and corrective action.
- Keep technical causation separate from personnel or legal conclusions.
- Write reports so each major conclusion traces back to evidence and each action traces back to a verified cause or failed control.
- Communicate uncertainty proportionally rather than overstating certainty.
- Translate lessons learned into specific changes to design, construction, verification, change management, or maintenance.

Glossary of investigation terms

Adverse condition: An observed state or event that may require engineering evaluation, such as distress, nonconformance, performance shortfall, or incident.

Barrier / control: A design, process, inspection, testing, review, monitoring, or management feature intended to prevent, detect, or limit an unacceptable condition.

Baseline: The expected or reference condition used for comparison, such as design geometry, approved sequence, specified property, or initial survey reading.

Contributing factor: A condition that increases the likelihood or severity of the event but may not be sufficient by itself to produce the outcome.

Correction: Action taken to fix a specific detected nonconformance or defect.

Corrective action: Action taken to eliminate or control a verified cause or failed control so recurrence risk is reduced.

Effectiveness verification: Evidence-based check that a corrective action has been implemented and is producing the intended sustained control.

Evidence gap: Information that is unavailable, unreliable, altered, or insufficient to resolve a material investigation question.

Failure mechanism: The physical or functional process by which performance departed from the intended condition.

Hypothesis: A proposed explanation that can be tested against supporting and contradicting evidence.

Immediate / proximate cause: A cause close to the event in time or physical sequence; it may not explain why the condition existed or escaped control.

Nonconformance: Failure to meet a specified requirement, tolerance, acceptance criterion, approved detail, or other controlling project requirement.

Problem statement: Neutral description of what happened, where, when, and to what extent, written without embedding an unverified cause.

Root cause: A verified underlying causal condition that, if effectively addressed, reduces the likelihood of recurrence; complex events may have more than one root or systemic cause.

Systemic cause: A broader organizational, process, interface, or control condition that permits similar causal conditions to occur beyond one isolated event.

Traceability: Ability to connect evidence to findings, findings to conclusions, and conclusions to disposition or corrective action.

Uncertainty: A limit in knowledge about condition, parameters, sequence, evidence quality, or causal interpretation that should be considered in the engineering decision.

Principal references

The following sources support the investigation, documentation, quality, and transportation context used in this course. They are reference frameworks rather than substitutes for the controlling documents on a specific project. Verify current editions, revisions, project incorporation, and agency requirements before professional application.

- Federal Highway Administration (FHWA), Construction Program Management and Inspection Guide. FHWA guidance emphasizes planned construction inspection, fact development, documentation, follow-up, and the role of quality assurance in Federal-aid construction oversight. Open source
- 23 CFR Part 637, Subpart B - Quality Assurance Procedures for Construction. Federal requirements governing quality assurance for materials and construction on Federal-aid highway projects on the National Highway System. Open source
- Florida Department of Transportation (FDOT), Construction Project Administration Manual (CPAM), Procedure 700-000-000. Current portal and chapter revisions; searchable complete manual updated August 4, 2026. Open source
- FDOT, Standard Specifications for Road and Bridge Construction, FY 2026-27, effective July 1, 2026, plus applicable revisions and project-specific supplemental specifications. Open source
- U.S. Army Corps of Engineers, ER 1180-1-6, Construction Quality Management, issued February 6, 2025 and effective March 6, 2025. Open source
- National Transportation Safety Board (NTSB), The Investigative Process. High-level transportation investigation model covering notification, on-site fact gathering, analysis, probable-cause determination, reporting, and safety recommendations. Open source
- Applicable project-specific drawings, specifications, calculations, geotechnical data, shop drawings, submittals, RFIs, inspection records, laboratory and field testing data, survey information, approved changes, as-built records, and maintenance/operations records. Project-specific controlling documents take precedence over generic examples in this course.
- Applicable AASHTO, ASTM, ACI, ASCE/SEI, and other engineering standards or codes when relevant to a project or case example. Because editions and contract incorporation vary, the engineer should verify the specific controlling edition and project requirement before applying a standard.
- NTSB — Collapse of I-35W Highway Bridge, HAR-08/03 (2008). Investigation evidence and Figure 15, printed p. 20.

Reference editions and public source links checked November 15, 2026. Apply the governing project documents and incorporated editions to professional work.

> **Study guide complete.** Return to the BuilderCE lesson page and select Continue to begin the final examination. A score of at least 70% is required to pass. Retakes are permitted.