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Construction of Buildings and Infrastructure over Active Faulting Zones

A Thesis Submitted in Partial Fulfilment of the Requirements
for the Degree of Master of Science (Laurea Magistrale) in

Civil Engineering for the Mitigation of Risk from Natural Hazards

by

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ABSTRACT

Surface-fault rupture represents a distinct seismic design challenge because it imposes permanent ground displacement (PGD) rather than transient inertial demands. Consequently, conventional force-based seismic design does not directly address the governing compatibility problem created by active faulting zones. In many jurisdictions, the absence of codified deformation-based procedures has encouraged reliance on setback prohibitions. However, for infrastructure corridors and dense urban areas, avoidance is frequently constrained, motivating the need for a structured synthesis of feasible engineering responses under realistic uncertainty.

This thesis organizes engineering practice for construction across faulting zones around three response concepts, illustrated through three representative asset classes. For ordinary buildings, the dominant feasible approach is rigid-body tolerance, where robust continuous foundations such as rafts redistribute support and promote coherent deformation, often preserving life-safety while accepting permanent rotation, settlement, and serviceability loss. For buried pipelines, the most mature pathway is displacement-compatible detailing, in which fault movement is treated explicitly as imposed deformation demand and verified using strain acceptance criteria within soil–pipe interaction models. For road corridors, the prevailing strategy is sacrificial zoning with rapid recovery, concentrating damage within a defined crossing segment and enabling restoration through repair, regrading, and operational planning.

Across all three classes, the thesis demonstrates that the practicality and credibility of mitigation strategies depend critically on-site characterization: fault location should be treated as a positional envelope, deformation as distributed across a shear band, and displacement as directional and uncertain. This work therefore links engineering choice to achievable investigation resolution by proposing graded investigation levels scaled to project consequence. The principal contribution is a decision-oriented synthesis showing how performance objectives, investigation outputs, and response concepts interact, providing a structured basis for selecting avoidance, tolerance, or compatibility strategies where active faulting cannot be excluded from the built environment.

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Active Fault	A fault that has demonstrated movement in the geologically recent past, as defined by the governing scientific or regulatory body. Most definitions commonly use a threshold of movement within the Holocene, i.e., the last ~10,000 years
Displacement-Compatible Design	An engineering approach in which structural systems are designed to tolerate imposed displacements through controlled deformation, ductility, and flexibility, rather than relying primarily on strength or force resistance.
Fault Trace	The line where a fault plane intersects the ground surface.
Faulting Zone	A corridor of land surface where strain is accommodated across one or more fault strands, fractures, and damaged rock. While it often includes the mapped traces of past movement, future seismic rupture does not always localize on those same strands and may nucleate or propagate along previously unmapped or newly formed structures within the broader zone.
Hanging Wall	The upper block of a dipping fault plane, typically experiencing uplift in reverse faults and downward motion in normal faults.
Permanent Ground Displacement-PGD	Lasting, non-reversible ground displacement produced by fault rupture.
Secondary Ruptures	Distributed cracks, fissures, or minor offsets that occur away from the principal fault trace.
Setback Distance	A regulated horizontal buffer measured from a mapped fault trace within which new construction is prohibited.
Shear Band	A zone of shear strain where most near surface deformation is localized as seismic fault rupture occurs. Its width, depth, and orientation strongly influence foundation response.

Soil–Structure Interaction	The coupled response of a structure and the supporting soil under imposed loading, where the deformation and stiffness of each system directly influence the behavior of the other.

1. Introduction

1.1 MOTIVATION

Construction over active seismic faulting zones represents one of the most complex and least addressed problems in earthquake engineering. While seismic design codes provide mature approaches for structural response to ground shaking, they offer limited and often indirect guidance for permanent ground deformation (PGD) associated with surface-fault rupture. In practice, many jurisdictions respond through avoidance-based land-use controls, including setbacks or prohibitions on building above mapped faults. Yet, in dense urban regions and along linear lifelines, complete avoidance is frequently impractical. This mismatch between hazard, regulatory controls, and available engineering design guidelines motivates the present research.

1.2 KNOWLEDGE GAP

Despite extensive academic progress in understanding soil–fault–foundation interaction, there is still no widely -adopted engineering framework that translates this knowledge into clear design criteria for conventional buildings. In practice, national regulations rely mainly on geological investigation requirements and setback-based avoidance rules, yet they offer limited guidance for cases in which avoidance is impractical or economically unfeasible. Conversely, academic models describe deformation mechanisms and foundation behavior in depth, but these results are rarely presented as clear inputs and verification steps that support routine engineering decisions.

1.3 RESEARCH QUESTION

Which engineering principles can be derived from the current academic understanding of fault-rupture mechanics and foundation behavior, and how can these principles be integrated with geological investigation practices and existing regulatory constraints to minimize structural risk within the uncertain shear band of active faults?

1.4 CONTRIBUTION

This thesis contributes a decision-oriented bridge between regulation, investigation practice, and engineering design for construction near active faults. It first provides a structured comparison of regulatory approaches in five jurisdictions, highlighting how setbacks and avoidance are implemented and why they vary. It then identifies the fault-rupture information that engineers and planners actually need and evaluates common investigation methods by their ability to provide that information at project scale. Building on this, the thesis proposes a graded set of investigation levels linked to project consequence, making uncertainty explicit and usable in decision-making. Finally, it synthesizes feasible engineering response concepts and demonstrates how they apply differently to buildings, buried pipelines, and road corridors when avoidance is impractical or uneconomical.

1.5 STRUCTURE OF THE THESIS

This thesis is organized to move from problem framing and policy context, through technical information requirements, to a synthesis of feasible engineering responses for construction in active fault-rupture environments.

Chapter 2 establishes the regulatory foundation of the thesis by comparing how five jurisdictions manage development in active fault zones as a risk management problem. It reviews national frameworks in Israel, California, Turkey, Taiwan, and New Zealand, focusing on how each system attempts to reduce future risk by limiting exposure through setbacks, zoning overlays, and site investigation triggers. The chapter evaluates the practical consequences of these approaches in developed settings, where existing urban exposure and infrastructure corridors constrain the feasibility of strict avoidance as a risk management strategy, and where regulatory decisions become explicit trade-offs between safety, economic cost, and land-use feasibility. The chapter concludes by synthesizing cross-country patterns, showing how different institutional and cultural contexts lead to different balances between prohibition to flexible management of residual risk.

Chapter 3 defines the critical information that engineers and planners require in order to make knowledged siting and design decisions under fault-rupture hazard. It identifies the key categories of fault-rupture input needed to manage uncertainty and reduce decision error at the project scale, and it evaluates investigation methods according to their practical ability to deliver usable constraints of the problem. The chapter then examines how far existing regulatory systems actually require such information, highlighting a recurring gap between the intent to control risk and the limited specification of investigation outputs that would support construction effort. It recommends a consequence-based set of investigation levels that explicitly links project importance to the expected reduction in uncertainty, thereby clarifying when risk can be managed through engineering accommodation and when avoidance remains the rational risk-reduction strategy.

Chapter 4 develops the structural engineering scope by treating surface-fault rupture as a permanent deformation demand that challenges conventional building practice. It introduces three response concepts and demonstrates their application to ordinary buildings, buried pipelines, and road corridors. The chapter shows how these systems differ in deformation capacity and recovery expectations, and it draws out the practical implications for selecting a response strategy under constrained site information and inevitable uncertainty.

AI-based tools were used to support proofreading (spelling/grammar/style) and to assist in translating non-English sources. This enabled broader multilingual consolidation than would otherwise have been feasible. All ideas, interpretations, and conclusions are the author’s own. Translations were cross-checked using other tools and, where possible, against original texts; nonetheless, minor translation inaccuracies may remain. English and Hebrew sources are therefore considered the most reliable basis for exact phrasing and nuance.

2. National Regulation

Surface rupture is a low-probability but high-consequence hazard: rare in occurrence, yet catastrophic when it strikes. Unlike shaking, which every building code now addresses, rupture control lies at the intersection of engineering, planning, and politics. Its regulation raises questions not only of safety but of land use, property rights, and economic development. This explains why nations facing the same geologic threat have chosen very different regulatory paths.

Throughout history, many settlements were founded directly on active faults—examples include ancient cities along the Dead Sea Transform or in Anatolia. Even younger urban landscapes like California and New Zealand, major cities such as Los Angeles and San Francisco expanded across the San Andreas Fault only in the last two centuries. It was only in the late twentieth century, after events such as the 1971 San Fernando earthquake in California or the 1999 Chi-Chi earthquake in Taiwan, that nations began to treat fault rupture as a distinct hazard requiring its own legal response. In this sense, regulation of surface rupture is a relatively new chapter in seismic risk management, emerging only after societies confronted the reality that rebuilding in place perpetuates vulnerability

Surface-fault rupture presents a special category of seismic hazard: while shaking can be mitigated by structural design, rupture physically breaks the ground beneath structures. It is less well studied, usually associated with earthquakes that have long return periods, and is therefore harder to capture in conventional building practice. In principle, an engineer would need a performance-based code to handle rupture correctly-something most countries are yet to adopt. In such high-hazard environments, the correct engineering decision may not be to resist the hazard but to minimize exposure altogether. A ban on construction directly on top of active faults therefore appears, from a risk-assessment perspective, to be a rational and sometimes necessary strategy.

This chapter explores how five countries have attempted to regulate building and infrastructure development across active faulting zones. The subsequent sections review the national frameworks of Israel, California in the USA, Turkey, Taiwan, and New

Zealand, highlighting how different political, cultural, and engineering contexts have shaped these restrictions.

2.1 ISRAEL – NATIONAL CODE FAULT SETBACK

2.1.1 Historical Background

Israel lies astride the Dead Sea Transform, the plate boundary between Africa and Arabia, and has a long record of destructive earthquakes. The events of 749 and 1837 CE devastated Tiberias and Beit She'an, both of which sit directly on mapped fault traces (Lazar et al., 2022). Despite this, the modern population, composed largely of third-generation immigrants from non-seismic regions mostly, has little lived memory of such disasters. Aside from the 1995 Gulf of Aqaba earthquake, which caused damage to an hotel in Eilat, no catastrophic event has occurred in living memory of the state.

The result is a public with low seismic awareness and minimal political pressure for resilience (State Comptroller, 2012; 2018; 2024). Earthquake safety has remained marginal in government planning.

The national seismic code SI 413 was first adopted in 1980 and became fully enforceable in 1995 (Shohet et al., 2016). For decades it addressed ground shaking only. In 2013, the 5th Amendment introduced the Israeli Geological Survey's map of active and suspected faults as a normative annex, and a 15 m setback from active faults, creating for the first time a regulatory reference to surface rupture (SI 413 Amendment 5, 2013).

In 2023, following the Turkish earthquakes felt in Israel, the 10th Amendment imposed a sweeping prohibition: a 100 m setback on soft soil and 15 m on rock from any suspected active fault (SI 413 Amendment 10, 2023). This is while the faults sit alongside the Jordan river and naturally characterized by deep alluvial soil layers, without distinguishing secondary and primary faults system. The 100 m arbitrary measure was taken from a single case of the Turkish seismic disaster and applied in the Israeli national code without proper adjustment.

2.1.2 Regulatory Provisions

Key elements of the current provisions are:

Prohibition of all new construction within 100 m of a suspected active fault trace in soil, or 15 m on bedrock.

Exception only if a licensed geological investigation demonstrates inactivity.

The regulation applies universally to all building uses, except for "low-rise" structures that translate to small storage or agricultural buildings, which remain exempt from seismic design all together as well as faulting.

The mapping authority rests with the Geological Survey of Israel, whose 1:50,000 fault map defines which traces are considered active or suspected (Rosensaft & Sagy, 2019).

2.1.3 Pre-existing development in faulting zones

Unlike many younger nations, many of Israel's cities are ancient and cannot be shifted away from their foundations. Tiberias and Beit She'an both straddle active faults, and large parts of their built fabric and infrastructure stand directly within rupture zones (Lazar et al., 2022). The Haifa metropolitan area is also bisected by the Yagur fault, which passes through industrial facilities and dense neighborhoods (Ben-David, 2004). This fault is only a secondary fault to the large Dead Sea system and could have been suited with less strict setback.

Highways, pipelines, and utilities follow the Jordan Valley and Dead Sea corridors, paralleling faulting zones for long distances. The new provisions do not apply retroactively, leaving existing exposure largely unmitigated, and since construction is forbidden, without a permission of mitigation.

2.1.4 Implementation in engineering practice

Since 2013, engineers have been required to consult the Israeli Geological Survey's fault map when designing projects (SI 413 Amendment 5, 2013). Because the official layer was created for academic purposes at 1:50,000 scale, it often misplaces traces by hundreds of meters relative to the property scale. Yet the regulation requires precision at the 15–100 m level, creating conflict.

In practice, engineers employ three strategies:

1. Locating the fault more precisely using trenching, geophysics or boreholes to see whether the mapped line is misplaced.
2. Soil profiling to demonstrate rock conditions, which reduce the buffer from 100m to 15m.
3. Challenging activity status, sometimes showing that a mapped fault was inferred (e.g. from hot springs activity) without physical fault evidence. In such cases, the Geological Survey may update its GIS layer and remove restrictions.

These practices reflect an effort to "translate" academic mapping into engineering terms. Without such site-specific work, projects in cities can be paralyzed by the blanket buffer zones, such is the case of the airport in Eilat which was removed from the city center for hotels and residence but when 4 faults line were found in its area, only a public park could be built in its stead.

2.1.5 Critiques and economic impacts

The 2023 setback triggered strong opposition from the engineering and development sectors. Critics argue that:

The 100 m corridor is arbitrary, introduced without proper technical consultation (SI 413 Amendment 10, 2023).

The rule depends on maps of inadequate accuracy and purpose, leading to misplaced restrictions.

The economic implications are severe in a densely populated country where developable land is scarce, and many cities' centers are built around fault traces.

Professionals also stress that SI 413 is not a performance-based code. It has no provisions for designing against rare fault rupture by displacement-compatible methods. Instead, it adopted the “easy solution” of banning construction outright.

Meanwhile, the larger vulnerability remains unresolvable since construction is banned where the rupture is possible: the State Comptroller warns that 93% of at-risk buildings would collapse in a strong earthquake (Times of Israel, 2023). Critics argue that banning new development near faults does little to address the far greater already existing hazard of faulting PGD.

2.1.6 Assessment

Israel’s regulatory path demonstrates how seismic policy can be shaped by history, demography and politics. With a population largely unaware of the seismic hazard, no catastrophic event in living memory, and ancient cities fixed on faulting zones, regulation has evolved through reactive steps rather than proactive planning.

The strengths of the current system are clarity, nationwide uniformity, and legal authority. Its weaknesses are rigidity, economic cost, and dependence on uncertain mapping. Engineers continue to seek flexibility through site-specific studies, but the code remains limited by its non-performance-based character. By prohibiting construction within setback zones, the regulation effectively prevents retrofitting or strengthening of existing structures already located in potential faulting zone, leaving the most hazardous locations unaddressed.

2.2 CALIFORNIA - POST EARTHQUAKE FAULT ZONING ACT

The State of California in the USA has provided the most enduring and widely studied legal framework for controlling construction across active faulting zones. The Alquist–Priolo Earthquake Fault Zoning Act (A-P Act) was adopted in 1972 as a direct response to the destructive 1971 San Fernando earthquake, which produced extensive surface rupture and caused collapse of hospitals and freeway interchanges (Olshansky, 2001). The statute's primary objective is to prevent the positioning of new structures for human occupancy directly over active faults or in close proximity to them, thereby reducing the hazard of surface-fault rupture (California Public Resources Code, 2621–2630).

2.2.1 Historical Background

Prior to 1972, California had introduced isolated seismic safety legislation. The Field Act of 1933 imposed structural standards for schools. hospital safety laws followed in the 1960s. However, there was no systematic land-use control on faults. The San Fernando event was a turning point. it triggered the creation of the California Seismic Safety Commission (1974) and ultimately the A-P Act (Palm, 1981).

Because it was drafted and adopted by politicians rather than engineers, the Act was inherently shaped not only by technical risk assessments but also by wider public concerns. Economic feasibility, property rights, and cultural expectations of land use all influenced its design. This political origin explains both the strength of the Act and its compromises, such as exemptions for small dwellings and the decision not to mandate removal of pre-existing buildings.

The Act mandated the State Geologist to map "Special Studies Zones" (later renamed Earthquake Fault Zones) along Holocene-active faults, initially covering the San Andreas, Hayward, Calaveras, and San Jacinto faults systems. The policies and criteria used for this mapping were to be established by the State Mining and Geology Board, a public oversight body within the Department of Conservation that sets statewide standards for geologic hazard mapping and land-use regulation.

In 1975 the legislature amended the Act to require disclosure to property buyers: real-estate agents or sellers must inform prospective purchasers if a property lies within a mapped zone (Palm, 1981). This provision was politically sensitive but passed as part of a compromise package that also exempted small single-family dwellings and minor alterations from the reporting requirement.

2.2.2 Regulatory Provisions

The law applies to two project categories: (i) subdivisions that contemplate future human-occupancy structures, and (ii) buildings for human occupancy themselves (California Public

Resources Code, § 2621.6). Within Earthquake Fault Zones, permits are conditional on a site-specific geologic investigation performed by a licensed geologist. If an active fault trace is present, buildings cannot go over the fault's trace and must be set back. In practice, most jurisdictions adopt setbacks of 50 ft (15 m), though the law itself does not prescribe an exact distance (California Department of Conservation, 2019).

The Act explicitly excludes certain cases: single-family dwellings not part of larger developments, small architectural alterations below 50 % of building value, and pre-1975 structures, which may remain even if directly stationed over a fault (California Public Resources Code, § 2621.7). Historic buildings may obtain exemptions if seismically retrofitted. In any situation, property sellers must inform buyers that the property is located in the fault zone.

Enforcement is delegated to cities and counties, which integrate the Act into zoning ordinances and general plans. The State Geologist provides official zone maps, which must be displayed at county offices (California Public Resources Code, § 2622). However, the state does not conduct routine peer review of site investigations, leaving quality control to local authorities (Olshansky, 2001).

2.2.3 Pre-existing development in faulting zones

A major challenge for the Alquist–Priolo framework was that, by the time it was enacted in 1972, large portions of California's urban land had already been built directly on active fault traces. In metropolitan Los Angeles and the San Francisco Bay Area, subdivisions and commercial tracts had expanded across the San Andreas, Hayward, and other major faults systems during the housing booms of the 1950s and 1960s (Palm, 1981). When the first official Earthquake Fault Zone maps were issued between 1974 and 1976, they confirmed that many existing neighborhoods fell inside the newly drawn zones (Olshansky, 2001).

Because of this, the Act could not function as an absolute prohibition on all construction within the mapped areas. Instead, it focused on regulating new development while allowing pre-existing structures to remain. These already existing properties highlight one of the Act's inherent limitations: the hazard could not be eliminated where people were already living on it (California Department of Conservation, 2019). Later planning studies observed that in Los Angeles, by the 1990s, more than 60 % of the city's land was covered by one or more seismic hazard designations (e.g. faulting, liquefaction or landslide), making blanket avoidance strategies unfeasible (Olshansky, 2001).

This historical context explains why the Act adopted a relatively flexible approach in dense urban areas, relying on geological investigation, disclosure, and setbacks, while being applied more strictly in sparsely populated regions where development could be steered away from fault zones altogether.

2.2.4 Implementation in engineering practice

For structural engineers, the Act means that most conventional buildings must avoid fault traces altogether, while infrastructure projects that must cross them, such as pipes roads and bridges, are designed for displacement compatibility. For example, the California Department of Transportation (Caltrans) requires a displacement hazard analysis where bridges intersect Alquist–Priolo zones. At Alder Creek Bridge, on the North Coast section of the San Andreas Fault, engineers adopted a design displacement of 18 ft right-lateral and 1 ft vertical offset, based on probabilistic and deterministic analyses (Caltrans, 2013). Design adaptations included wider expansion seats, ductile reinforcement, and continuity details.

2.2.5 Critiques and economic impacts

Critics have highlighted several limitations. First, disclosure requirements proved largely ineffective: surveys revealed that fewer than half of buyers recalled being informed, and few changed their behavior or sought insurance (Palm, 1981). Second, exemptions for small dwellings and legacy developments meant that new houses were sometimes still erected on active faults (Olshansky, 2001). Third, uneven enforcement across counties, combined with a lack of mandatory state review, created inconsistencies and potential developer influence over the geological site-specific study.

Economic studies anticipated significant devaluation of property within fault zones (Gillies, 1976), but empirical work showed minimal long-term price effects. Buyers prioritized investment potential and location over hazard disclosure, and very few transactions collapsed due to the Act (Palm, 1981). As a result, the feared economic harm did not materialize, but nor did the law create strong financial incentives to avoid high-risk sites.

Despite these limitations, the Act has contributed to risk reduction at the state scale. By prohibiting new structures for human occupancy directly across active fault traces, it has prevented the addition of thousands of buildings in locations with rupture damage in a major earthquake, thus directly reducing exposure. For infrastructure, the requirement to evaluate and design for fault displacement has led agencies such as Caltrans to adopt displacement-compatible practices, thus reducing infrastructure vulnerability. Although the benefit is difficult to quantify in risk terms, this systematic avoidance and adaptation represent a significant reduction in California’s long-term economic and life losses to surface-fault rupture hazard.

2.2.6 Assessment

The Alquist–Priolo Act represents a pragmatic, map-triggered land-use control that has endured for half a century. Its strengths lie in preventing the most dangerous siting of new buildings directly across active faults and institutionalizing fault-aware subdivision design. Its weaknesses stem from uneven enforcement, ineffective disclosure, and residual risks from earlier construction. For structural engineering, it provides a regulatory baseline: ordinary occupancy must be set back, while infrastructure must explicitly accommodate expected fault displacements.

2.3 TURKEY - POST EARTHQUAKE FAULT ZONING ACT

2.3.1 Historical Background

Turkey sits astride the North Anatolian, East Anatolian, and other active fault systems, producing frequent destructive earthquakes. The 1939 Erzincan and 1999 Marmara earthquakes, and most recently the 2023 Kahramanmaraş, demonstrated the devastation of surface rupture through populated settlements (Aydan et al., 2024).

Early legislation such as Law 7269 on “Measures to be Taken due to Disasters Affecting Public Life” (1959) provided authority to designate Disaster-Prone Areas (Afete Maruz Bölge) where construction is prohibited (Gürboğa et al., 2016). In practice, however, these provisions were used inconsistently and rarely applied to active faults.

From the 2000s onward, municipalities began to require geotechnical investigations for zoning plans, including mapping of active faults (AFAD, 2023). Professional organizations such as the Chamber of Geological Engineers (JMO) published technical criteria for fault hazard zones and sakınım bands (setback corridors) (JMO, 2017). Yet without a national framework, implementation varied widely across cities (Şevkin, 2023). The catastrophic 2023 earthquakes triggered a paradigm shift: the Disaster and Emergency Management Presidency (AFAD) issued a binding circular establishing a nationwide ban on construction over active fault traces.

2.3.2 Regulatory Provisions

Post-earthquake reconstruction measures introduced under Law No. 7452 required settlement and reconstruction planning to consider proximity to active faults and ground suitability, while subsequent ministry policy adopted a zero-tolerance approach to new construction directly on mapped fault traces (Republic of Türkiye, 2023). Fault corridors are to be reserved as Fault Preservation Belts and integrated into local development plans. Infrastructure that must cross a fault may be permitted, but only with displacement-tolerant design.

Technical guidance for defining fault avoidance zones derives from the JMO 2017 Guide, which recommended buffer widths depending on fault type and certainty: typically 20 m on each side for well-mapped strike-slip faults, up to 60 m total (15 m on the footwall, 35–45 m on the hanging wall) for normal faults, and larger if the trace is uncertain (JMO, 2017). These recommendations align with international practices such as California's Alquist–Priolo Act and New Zealand's Fault Avoidance Zones (Boncio et al., 2011; Kerr et al., 2003).

A permanent Fault Law has been drafted, intended to amend Law 7269 by explicitly banning construction in surface-fault rupture hazard zones nationwide (İMO, 2020). As of February 2024, however, the draft had not been enacted by Parliament, and no subsequent evidence was found to confirm its passage since (Teyit, 2024).

2.3.3 Pre-existing development in faulting zones

Many Turkish cities have extensive pre-existing settlement across active faults. In İzmir, residential districts sit astride the İzmir Fault; in Erzincan, town quarters overlie the 1939 rupture; in Hatay, Antakya's urban fabric coincides with East Anatolian fault traces (Aydan et al., 2024). In Sakarya's Akyazı district, an initial 150 m-wide no-build corridor was later reduced to 20 m under local pressure, illustrating difficulties in sustaining avoidance measures (Gürboğa et al., 2016).

Because the AFAD ban applies only to new development, existing exposure remains. Law 7269 provides authority for relocation, but large-scale removal of at-risk buildings is politically and financially challenging.

2.3.4 Implementation in engineering practice

Over the past decade, and especially after the 2020 Elazığ and 2020 İzmir earthquakes, the Turkish geotechnical and seismological community has been heavily engaged in fault investigation. Universities, MTA, and AFAD initiated large-scale projects combining geomorphological mapping, geophysics, and paleo-seismology. Trenching campaigns multiplied along the East Anatolian and North Anatolian fault systems, producing dozens of new slip-rate estimates and confirming rupture geometries (Aydan et al., 2024).

At the planning scale, regulations since 2004 have required geotechnical–geological investigations at 1:5000 and 1:1000 scales. These investigations now routinely integrate LiDAR, UAV photogrammetry, shallow geophysics, and borehole logging to refine fault positions before zoning plans are approved. The community's accumulated experience with these techniques has greatly improved the reliability of fault trace location compared with earlier 1:250,000 or 1:100,000 scale maps (Gürboğa et al., 2016).

Following the 2023 Kahramanmaraş earthquakes, AFAD and MTA launched an unprecedented cooperative program with 24 universities to investigate 132 active faults across the country using paleo-seismic trenching and remote sensing. This surge of activity has both expanded the database of active faults and trained a new generation of Turkish geotechnical engineers and geologists in advanced surface rupture investigation methods (AFAD, 2023).

In practice, once a fault trace is confirmed by these methods, a buffer zone extending outward from the fault zone on each side is delineated in the zoning plan, and construction is forbidden within it. Infrastructure projects that must cross these zones are required to demonstrate displacement-compatible design. The 2023 AFAD directive standardized this practice nationwide, making fault corridor avoidance mandatory.

2.3.5 Critiques and economic impacts

Critiques of the Turkish framework focus on three issues:

- Inconsistency: Before 2023, application of fault setbacks varied widely between municipalities, creating legal uncertainty for developers (Gürboğa et al., 2016).
- Enforcement: Even after the AFAD ban, reports indicate non-compliance in some provinces, where economic pressures outweighed safety (TMMOB, 2023).
- Remaining exposure: Millions already live in fault-crossing settlements; banning new development does not reduce this inherited vulnerability (Şevkin, 2023).

Economically, the setback corridors remove valuable urban land from development. However, cost–benefit analyses suggest that preventing catastrophic rupture damage outweighs the opportunity cost, particularly in dense cities (Smyrou et al., 2024). In the 2023 earthquakes, buildings directly straddling ruptures were destroyed regardless of structural strength (Aydan et al., 2024).

2.3.6 Assessment

Turkey's regulatory trajectory reflects both reactive disaster response and growing scientific capacity. The 2023 AFAD supplement created, for the first time, a uniform nationwide construction ban on active faulting zones by an administrative order while the parliament is struggling to do so. Its strength lies in clarity and legal enforceability, supported by ongoing high-resolution mapping and trenching programs. Its weaknesses are the lack of parliamentary codification, uneven enforcement, and unresolved legacy exposure.

The current system's main strengths are its clarity, national scope, and the unprecedented technical momentum within the geotechnical community. Its weaknesses lie in its reliance on executive orders rather than law, variable enforcement, and the difficulty of addressing existing settlements. Turkey therefore stands at an important juncture: the ban is in place, expertise is growing, but long-term resilience depends on codifying these measures into law and developing strategies to mitigate pre-existing risk.

2.4 TAIWAN – ACTIVE FAULT REGULATIONS

2.4.1 Historical Background

Taiwan occupies a tectonically active boundary where the Philippine Sea Plate collides with the Eurasian Plate, making earthquakes a familiar feature of life in Taiwan. The population was accustomed to frequent shaking, particularly in the eastern counties of Hualien and Taitung, where offshore earthquakes are common. Yet during the second half of the twentieth century, no catastrophic inland earthquake struck the island. The last comparable disaster was the 1935 Hsinchu–Taichung earthquake (Mw 7.1), which killed more than 3,000 people. By the time the Republic of China government had re-established itself in Taiwan after 1949, it had not faced a devastating inland rupture. For this government, the 1999 Chi-Chi earthquake therefore came as the first true national-scale seismic crisis.

Chi-Chi (Mw 7.7) ruptured the Chelungpu Fault across nearly 100 km, with dramatic surface offsets cutting through towns, schools and infrastructure in Nantou and Taichung counties. More than 2,400 people were killed, 100,000 left homeless, and entire neighborhoods displaced along the fault trace. The earthquake demonstrated that settlements, both traditional towns and later expanding cities, had grown directly across active faults. While Taiwanese society was used to frequent tremors, Chi-Chi exposed how unprepared the state was for surface rupture through urban land, and it created the political momentum for a new regulatory framework.

2.4.2 Regulatory provisions

The regulatory framework that emerged after Chi-Chi was not a single reform but a long process involving several ministries and legislative acts. The central actors were the Ministry of the Interior (MOI), through its Construction and Planning Agency, and the Ministry of Economic Affairs (MOEA), through the Central Geological Survey.

Immediately after 1999, the MOI, operating as a direct arm of the central government, revised the Building Technical Rules to prohibit construction directly astride active faults. Article 262 defined setback distances according to the largest historical magnitude: 100 m on each side for faults with Mw ≥ 7, 50 m for Mw 6–7, and 30 m for smaller or unproven traces (MOI, 2010). These rules were administrative instruments, issued under government order in response to public concern rather than technical initiative from professional associations.

In 2010, the Legislative Yuan passed the Geological Act, which empowered MOEA to designate ‘Geologically Sensitive Areas’ (地質敏感區) along active faults. This law gave parliamentary authority to the restrictions and required site-specific geological investigation and safety assessments for any land development inside the designated zones (Geological Act, 2010). Between 2014 and 2023, 25 fault zones were announced, covering about 183 km² (Audit Office, 2021). These announcements remain ongoing, and by 2021 only 20 of 36 known active faults had been zoned.

The process continued with amendments to the Building Act in 2018, requiring quake-resistance inspections and upgrades for large public-use buildings constructed before 1999. The sequence illustrates how Taiwan’s regulations evolved in layers: administrative rules after Chi-Chi, followed by a parliamentary Geological Act, followed again by continued audits and amendments. The path has been slow and cumulative rather than a sudden reaction to the disaster.

2.4.3 Pre-existing development in faulting zones

By the time these regulations were enacted, many communities already settled active faults areas. In Nantou County, public buildings were banned and only low-rise houses (≤ 2 storeys, ≤ 7 m) permitted within 15 m of the Chelungpu Fault (Taipei Times, 2016). Elsewhere, zoning overlays varied, and disclosure requirements for land titles were inconsistently applied. The restrictions created a paradox: hazardous structures remained standing in rupture zones, but new construction and retrofitting were prohibited, leaving the highest-risk land frozen in place (Chen et al., 2018).

2.4.4 Implementation in engineering practice

For engineers, active fault zones mean that major projects must undertake site-specific geological investigation—trenching, boreholes or geophysics—before permits are granted (CPA, 2018). Within 15 m fault corridors, only agricultural or low-rise housing is allowed, and public facilities are forbidden. Infrastructure may cross a fault only if it demonstrates displacement-compatible design (CPA, 2018; MOI, 2010).

Beyond these exclusion zones, revisions of the seismic code in 2005 incorporated near-fault effects into design loads, raising requirements even for projects outside the immediate corridors (Guy Carpenter, 2024). In Taiwan, these changes were introduced under direct order of government authorities, reflecting public demand for stronger rules after Chi-Chi rather than a profession-led process.

In the 2005 Taiwanese seismic design rules (building and infrastructure), near-fault effects are codified via adjustment factors N_A (short-period acceleration domain) and N_V (long-period velocity domain). These factors increase the spectral response accelerations (i.e.

amplify design forces) for structures close to active and mapped faults, and fall off with distance.

For example, in the bridge design specification for Chelungpu Fault, for sites within 2 km of the surface rupture, N_A=1.34 and N_V=1.70 (MOI, 2005; NCREE). At about 4 km, the factors drop to 1.16 and 1.30 respectively. For sites beyond 6 km, the values revert to 1 (i.e. no amplification). These are used for linear interpolation in between. Such values serve as a practical example of how near-fault demands are increased for infrastructure, and give a sense of order of magnitude for buildings under similar code requirements.

2.4.5 Critiques and economic impacts

Taiwan's system has drawn critique for its slow progress and uneven enforcement. By 2021, only about half of the known active faults had been zoned as sensitive areas (Audit Office, 2021). Builders' associations have argued that blanket bans waste valuable urban land and that reinforcement should be preferred over prohibition (Taipei Times, 1999). At the same time, the restrictions prevent renewal of dangerous housing stock in rupture corridors, locking in residual exposure. Nevertheless, the memory of Chi-Chi and subsequent earthquakes has sustained public and political support for the continuation of restrictions.

2.4.6 Assessment

Taiwan's regulatory trajectory illustrates a layered, government-driven process rather than a single act. The MOI established fault setbacks through the Building Technical Rules, the Legislative Yuan gave them statutory weight with the Geological Act, and the MOEA has gradually implemented zoning. These measures were initiated by government and public demand after the Chi-Chi earthquake disaster.

Taiwan's system combines parliamentary legitimacy with slow implementation: its strength lies in long-term legal authority, but its weakness is fragmentation, uneven enforcement, and unresolved existing exposure in hazardous locations.

2.5 NEW ZEALAND - REGULATIONS AND RISK-BASED MANAGEMENT

2.5.1 Historical Background

New Zealand's regulation of surface-fault rupture hazards is rooted in the Resource Management Act 1991 (RMA), which requires territorial authorities to control land use to avoid or mitigate natural hazards (Kerr et al., 2003). Rather than imposing a single national setback distance, the Ministry for the Environment's Active Fault Guidelines (2003) established a risk-based framework: planning should consider the return period of fault rupture, the complexity of the fault trace, and the importance category of the building (Kerr et al., 2003).

2.5.2 Regulatory Provisions

Implementation is passed down to district councils, which adopt Fault Avoidance Zones into their plans using mapping from Institute of Geological and Nuclear Sciences (GNS Science). For instance, in the Kāpiti Coast District, any landowner or developer proposing a new building within a mapped fault zone must apply for resource consent from the District Council, which decides whether to grant approval or impose conditions to minimize the risk if avoidance is impossible (KCDC, 2025). Similar overlays exist in Wellington, Porirua, and Upper Hutt. Rules typically distinguish between high-exposure uses (schools, hospitals, dense housing) and low-exposure uses (i.e. utilities, storage), with activity status scaling according to risk (Porirua City Council, 2021).

In Wellington City, the 2021 GNS Science active-fault study was integrated into the District Plan, producing detailed Fault Avoidance Zones across suburbs such as Thorndon and Aro Valley (Morgenstern and Van Dissen, 2021). The plan assigns activity status depending on three factors: the recurrence-interval class of the fault, the building importance category, and whether the site is in a greenfield or in an already developed area.

2.5.3 Pre-existing development in faulting zones

Because New Zealand was settled relatively late in modern history, only a handful of towns and cities were established directly across active fault systems. Wellington, Napier, and Blenheim are notable exceptions where major faults cut through existing suburbs. In these places, councils adopt pragmatic measures such as discouraging intensification, requiring disclosure, and mandating geotechnical assessments rather than enforcing removal (Morgenstern and Van Dissen, 2021). Elsewhere, most mapped fault traces lie in rural or undeveloped landscapes. Here, the planning framework can apply stricter avoidance rules, prohibiting new hazard-sensitive buildings in greenfield settings. The combination of a young urban history and an early national awareness of earthquake hazard allows New Zealand to direct much of its development into lower-hazard areas, while managing legacy exposure only in a few critical urban centres (KCDC, 2025).

2.5.4 Implementation in engineering practice

The Ministry for the Environment guidelines recommend that any proposed development within a mapped fault avoidance zone begins with a site-specific geological assessment. This usually means reviewing existing fault maps, carrying out a field inspection, and where necessary, confirming the fault trace by trenching or geophysical survey. The investigation results are then used to classify the fault's return period and to check the suitability of the project against the Building Importance Category tables. Councils use this information when deciding whether to grant consent and under what conditions. For major infrastructure, the Waka Kotahi Bridge Manual adds a further requirement: where avoidance is not possible, structures must be designed for displacement compatibility.

2.5.5 Critiques and economic impacts

The New Zealand framework, while widely regarded as a model of risk-based flexibility, has drawn critique on several fronts. Because the MfE Active Fault Guidelines are advisory rather than binding law, uptake has been uneven across territorial authorities. Some councils embed detailed Fault Avoidance Zones and activity-status tables, while others retain only general hazard provisions. This variability generates inconsistencies in how similar risks are managed across districts.

In densely populated settings, where avoidance is often impractical, critics argue that flexible rules allow too much residual exposure. In Wellington's Thorndon suburb, for example, large portions of the community remain sited directly across the Wellington Fault. Here, councils prioritise disclosure, site investigation, and consent conditions rather than strict avoidance, which has raised concerns about whether residual life-safety risk remains acceptable (Morgenstern and Van Dissen, 2021).

Uncertainty in hazard mapping and return periods adds further tension. Fault avoidance zones may span several hundred metres, later narrowed as new LiDAR or trenching data refine trace positions. Property owners perceive such changes as creating instability in zoning boundaries, which complicates investment decisions and often leads to calls for councils to ease or redraw the hazard restrictions.

Although plan overlays may reduce land value or restrict development options, especially for residential purposes, the absolute number and percentage of affected properties is very low compared with other seismic countries. Only a small fraction of New Zealand's building stock lies directly astride mapped active faults, and most fault traces cross rural or undeveloped land. As a result, while the financial impacts can be sharp for individual landowners, the overall burden on the national economy and housing market remains modest. At the local level, property owners may resist rezoning at first, but markets tend to stabilize once buyers see that development pathways remain open through resource consents (Porirua City Council, 2021; KCDC, 2025). For infrastructure, the requirement to incorporate displacement compatibility into bridges and lifelines does increase upfront costs, yet these measures are justified on cost–benefit grounds since designing for probabilistic offsets avoids catastrophic failures and total replacement in major rupture events (Dickson et al., 2022).

Overall, critiques centre on uneven implementation, residual exposure in cities, and short-term property impacts, while defenders stress that the framework delivers a pragmatic balance of safety and economic continuity.

2.5.6 Assessment

New Zealand's framework represents a mature application of risk-based flexibility. In sparsely populated rural landscapes, district plans can afford to prohibit or strongly limit new building near mapped faults. In dense urban centres, however, rules become more permissive: development may proceed with geotechnical verification and consent conditions. This creates a clear regulatory axis: the denser the population on or near a fault, the more flexible the restrictions. Rather than eliminating hazard exposure, the system manages risk by tailoring controls to building importance, return period, and site context (KCDC, 2025; Porirua City Council, 2021).

2.6 CONCLUSION

Across all five cases, the prohibition of new construction near faults has been chosen as a tool for reducing future risk, yet it has left a paradox: vulnerable older structures, often located in the most hazardous corridors, remain in place and cannot be retrofitted. In both Israel and Taiwan, limited exemptions permit low-rise agricultural or storage buildings, since these represent low exposure assets.

Looking at origins of regulation, three distinct groups emerge:

i) Disaster-driven systems: California and Turkey. Where sudden catastrophic earthquakes led to the imposition of restrictions by authority order, in a one simple order.
ii) Government and parliamentary legislation: New Zealand and Taiwan developed rules through government and parliamentary legislation, embedding them into planning frameworks over time and therefore considering different aspects of these regulation over time.
iii) Engineering code embedded - Israel stands apart as the only country where restrictions were introduced through the seismic code itself, a path led by engineers rather than political public institutions.

It was previously observed in New Zealand that the denser the development already present on or near a fault, the more flexible the regulation must become. In rural settings, councils could impose strict avoidance, whereas in Wellington compromises were made to allow continued occupation. This observation can be extended globally, with each case illustrating a different balance between flexibility and prohibition:

- California illustrates the limits of disaster-driven regulation in a heavily urbanized context. The Alquist–Priolo Act arose from the 1971 San Fernando earthquake, but by then Los Angeles and San Francisco were already deeply built over active faults. The law therefore functions less as an absolute prohibition and more as a procedure, easily adapted or bypassed in dense urban areas. In effect, California may be the most developed over active faults of all the examples, and this very density makes strict enforcement neither feasible nor politically sustainable, even though the 15m limit is the smallest of all 5 countries.
- Turkey illustrates a disaster authority response as well: the 2023 Kahramanmaraş earthquakes led AFAD to impose a strict nationwide ban. Yet enforcement remains uneven, and the presence of millions already living across faults forces pragmatic compromises. The tension between strict prohibition and lived urban reality is especially sharp here and awaits resolution.
- Taiwan shows a government-led process where restrictions became statutory through the Geological Act. It introduced different setback distances depending on fault magnitude, but still froze older, vulnerable buildings in place. This layered approach demonstrates both the strength of parliamentary authority and the limits of applying blanket bans.
- Israel is unique in embedding setbacks directly into the seismic code. Engineers rather than parliament introduced the restriction, producing a rigid ban that does not account for economic or cultural realities. Existing exposure remains unresolved, with the added difficulty that retrofitting is often prohibited by the same rule. The ban is also the widest of all cases, 100 m on each side of a fault, and it collides with the country's economic needs. Yet public criticism has remained muted, largely because the restriction affects poorer cities with little national leverage. The controversy only deepened after 2023, when the original 2013 rule was expanded to its current scope.

The size of the country also influences regulation. Smaller countries such as Israel and Taiwan can apply national rules across their territory, but this does not mean that a uniform ban is necessarily the best solution. More sophisticated approaches, such as varying setbacks by magnitude, mechanism, or wall side, would better align with engineering purposes and understanding. Larger countries such as Turkey, the USA, and New Zealand could delegate responsibility to regional or local authorities, since the complexity and diversity of their fault systems demand region-specific solutions. It is seen in these countries that when the regulation is uniform, the variation is then transferred to differential enforcements.

A promising future direction is the refinement of restrictions based on geologic and engineering criteria. Taiwan already adjusts setback distances by magnitude, while Turkish professional guidance suggests varying them by fault mechanism and by hanging wall versus footwall. If these approaches can be well coordinated with engineering practice, they offer a path toward regulations that are not only strict but also smart, balancing risk reduction with social and economic feasibility.

Taken together, these comparisons show that the most resilient regulatory paths are those established through legislation and layered over time. Such frameworks allow adaptation to cultural and economic realities, rather than attempting to impose sudden prohibitions after disaster. Where restrictions are introduced in reaction to catastrophe, as in California or Turkey, they are often difficult to enforce in densely developed areas. A country should not wait for a major earthquake to impose rules that will then be resisted or bypassed; instead, proactive and evolving legislation offers a more realistic path to reducing long-term exposure.

3. Geological Investigation for Seismic Faulting Hazard

Surface-fault rupture is primarily a geological phenomenon, but its importance in this thesis is as a load and constraint for structural and geotechnical design. Chapter 2 showed that most regulatory systems recognize active faults mainly through planning tools such as fault zones maps and setback corridors, while design standards focus on shaking. For structures that cannot simply avoid active faults, the missing link is a clear description of what information geological investigations should deliver to support displacement-compatible design.

This chapter explores that link from an engineering point of view. Section 3.1 identifies the set of parameters that are directly useful for siting and design decisions. Section 3.2 then reviews the main investigation methods that can be used to obtain this information. Sections 3.3 and 3.4 examine how far current practice goes in requiring such investigations. Finally, Section 3.5 uses this evidence to suggest a simple set of investigation levels, scaled by project importance. These levels are not a formal proposal, but they provide a practical framework for deciding how much fault-specific information can be expected at a given site and how it should be used in the displacement-compatible design strategies developed in Chapter 4.

3.1 INFORMATION REQUIRED BY ENGINEERS AND PLANNERS

Geological investigations for surface-fault rupture are carried out to provide a limited set of parameters that can be used directly in siting decisions and in displacement-compatible design. From a structural engineering point of view, the most important requirements fall into these groups.

Remote sensing and geomorphic mapping

Remote sensing and geomorphic mapping use aerial and satellite imagery, LiDAR, high-resolution DEMs, UAV photogrammetry and InSAR to map active faults and related landforms (Sun et al., 2022). In suitable terrain, meter-scale DEMs and LiDAR allow scarps and lineaments to be traced with roughly meter-scale accuracy and to distinguish individual strands and small bends that are not resolved on regional geological maps (Chen et al., 2015).

Displaced terraces, channels and anthropogenic markers provide cumulative offsets and slip-rate estimates, while multi-temporal optical and InSAR data resolve co-seismic displacement, post-seismic relaxation and, in some cases, interseismic creep and its distribution across the faulting zone (Liu et al., 2018). Erosion, sedimentation, vegetation and urban modification still remove many small secondary features, so in practice these methods usually define a minimum width of the shear band and only qualitatively constrain how displacement decays away from the main trace (Jamšek Rupnik et al., 2024).

The techniques are non-intrusive and practical at regional to site scales wherever suitable data exists, but they become less effective where the ground surface is strongly modified or obscured. They provide almost no direct constraint on depth: the dip and depth extent of the fault plane, deep branching, and the detailed layering and stiffness of near-surface deposits must be constrained by subsurface methods rather than surface imagery alone.

Fault trace location and sense of offset at site scale

For layout and design, the primary need is to know where active strands are relative to specific buildings or infrastructure. In practice, fault traces are not known as lines but as position envelopes with uncertainties that depend on available data. Within this envelope, it is important to distinguish between hanging wall and footwall, and between zones that are likely to experience the largest offsets and zones where deformation demand is lower. These distinctions control the type and level of deformation that structural and geotechnical design must accommodate at different parts of a site.

Width and distribution of the shear band

Surface rupture is seldom confined to a single sharp break. Secondary cracking, folding and warping may extend tens of meters or more away from the principal strand depending on the outcrop characteristics. Engineers therefore need at least approximate bounds on the width of the zone in which PGD can occur, and an understanding of whether deformation is typically concentrated in a narrow or spread belt. Even if this information is largely qualitative, it guides how deformation demand is assigned across a site, and whether only a narrow corridor is treated as having high displacement hazard or a broader zone needs to be considered.

Displacement metrics and directionality

Structural and lifeline design require numerical estimates of how much the ground may move and in which directions. This includes ranges of vertical and horizontal displacement that may occur in a single surface-rupturing event, and where possible, displacement expressed as a function of probability or return period in analogy with ground-motion hazard. For many systems, the directionality of slip is as important as its magnitude. Vertical steps, horizontal offsets parallel to the fault, and shear across the faulting zone have different implications for foundations, buried structures and surface connections. Engineers need to know not only how large the offsets can be, but whether vertical, horizontal or oblique components are expected to dominate at the site.

Faulting zone and cover structure

How rupture reaches the surface and interacts with foundations depends on the geometry of the fault system and on the thickness and properties of the near-surface deposits. Useful information includes whether the site lies above a single steeply dipping strand or within a complex zone of fissures, whether rock is present at shallow depth or buried beneath a thick cover of softer sediments, and whether strong contrasts in stiffness exist within the cover. These factors influence whether rupture is likely to be sharply localised or diverted beneath certain zones, and they frame the range of deformation patterns that design must consider.

3.2 CATALOGUE OF INVESTIGATION METHODS AND THEIR ENGINEERING VALUE

A wide range of geological and geophysical methods is available to investigate active faults. In this thesis, their usefulness is assessed not by theoretical resolution but by the quality and certainty of the information they provide for siting and foundation design. For each method, the review therefore focuses on these questions:

- Fault location- how precisely and reliably can the method constrain the position of active fault traces at the scale of a building or infrastructure footprint?

- Width and distribution of the shear band- how well can it define the width of the surface shear band and the rate at which displacement decays away from the principal trace?
- Displacement metrics- how precisely can it quantify expected single-event displacement and, where possible, express displacement as a function of magnitude, return period, or exceedance probability?
- Geometry and behavior of the faulting zone - what insight does it provide into the mechanism and layout of the faulting zone (e.g. branching, dip, segmentation) and into the properties of the overlying materials that control how rupture reaches the surface?
- Feasibility- how intrusive is the method, and how practical is it to apply on both greenfield and urban sites?

In each case, the discussion emphasises not only what a method can, in principle, reveal, but the typical uncertainty and bias in practice, and how safely its outputs can be used in planning setbacks and displacement-compatible design.

Desktop seismotectonic studies

Desktop studies compile existing geological maps, active-fault databases, earthquake catalogues and previous site-specific work, including paleoseismic, geophysical and even archaeological investigations where they exist. They are the starting line for almost every project because they are inexpensive, non-intrusive and can rapidly summarize what is already known about a site and its surrounding fault.

Their resolution and certainty are not fixed; they inherit the quality of the underlying investigations. In some areas with dense prior work, a desktop study may already provide tightly constrained fault locations, well-documented displacement per event and a clear picture of fault-zone geometry. In many others, information is limited to regional mapping and a few generic reports, so fault locations may be uncertain by tens to hundreds of meters and only broad fault corridors and order-of-magnitude displacement estimates are possible.

Field mapping and site visits

Field mapping and site visits are usually a complement to remote sensing and desktop studies rather than a standalone method. By walking the ground, checking exposures and measuring visible steps and cracks, they help confirm which features seen in images are active faults and which are landslides, old cuts or other man-made structures (McCalpin, 2009). At the scale of a building footprint, simple survey measurements can refine the location of the active strand to a few meters and give local observations of where secondary cracking and small scarps occur across the zone, anchoring the shear band at site scale but only sampling the parts that are visible at the surface.

Where clean exposures exist, field observations can also show local slip sense and contrasts between soils and rocks that may influence how rupture reaches the surface, but such cases are uncommon. Point measurements of offsets in small channels, paths or walls can indicate minimum single-event displacement, yet without knowing the age of these features they rarely provide full displacements histories or probabilities.

Field visits are manual and therefore time-consuming, so they are not efficient for large-area or detailed surveys, and most guidelines treat them as part of a broader site-specific investigation that also includes trenching or other subsurface methods (CGS Note 49, 2002). They give almost no direct information on the dip and depth extent of the fault or deeper branching, which must be constrained by trenches, boreholes or geophysical surveys rather than surface observations alone.

Paleoseismic trenching

Paleoseismic trenching excavates narrow trenches perpendicular to a suspected fault trace so that a vertical cross-section of the faulting zone and deformed layers in it are exposed and recorded (e.g. McCalpin, 2009). When the trench is well sited and oriented, the active strand can usually be located to within less than a meter, and closely spaced strands, small warping, and the thickness of the shallow damage zone can be seen directly at that section. Each trench, however, samples only a single section of the fault system, so the location and geometry it reveals are local and do not infer the entire strike geometry.

Offsets of buried soils or sediment layers across the fault allow individual surface-rupturing events to be distinguished and per-event displacements to be estimated. With dating of the faulted and unfaulted units, trenching can provide a local history of events and associated slip, giving some of the most direct displacement metrics available for design.

Trenching also reveals near surface-fault geometry, behavior and the layering of the overlying deposits, but only down to the trench depth, typically a few to several meters. Deeper structure and branching must be inferred from other methods. The technique is intrusive and requires machinery, safe shoring and site access, so it is rarely used for large-area surveys or in dense urban settings. In practice it is reserved for sites where regulations or project importance justify detailed on-fault investigation to confirm activity and obtain displacement histories.

Boreholes and associated in-situ tests

Boreholes, together with the various tests commonly carried out during or after drilling (sampling, CPT, SPT, and more), provide point information on soil and rock types, layering, strength, and related properties. In typical building and infrastructure projects these holes reach depths of a few tens of meters. Only in special studies do they extend much deeper. They therefore sample the shallow part of the faulting zone and cover, and not the full fault at depth.

Where a series of boreholes is drilled along a line or area, cores and logs can show where sheared material, repeated units or abrupt changes in soil or rock occur. By connecting information between boreholes, a shallow fault trace is inferred. Changes in layer thickness and properties along the line can also indicate how deformation is distributed across the zone, but everything between holes is interpolated, and branches or strands that are not intersected can be missed. Boreholes are therefore better at refining or confirming a trace suggested by mapping or remote sensing than at discovering unfamiliar fault systems. They rarely provide clear displacement metrics.

The main strength of boreholes and their associated tests is depth control: they give reliable layer thicknesses and depth to rock. They are intrusive and require drilling equipment, but the footprint is small, and they are often feasible even on dense urban sites. In many projects, fault-related questions can be addressed by slightly adapting the geotechnical borehole program that would be drilled for foundation design anyway.

Geophysical methods

Geophysical methods such as seismic reflection and refraction, MASW, ERT and GPR use contrasts in seismic velocity or electrical properties to image the shallow subsurface around a suspected faulting zone (e.g. McCalpin, 2009). These surveys are most often laid out along profiles roughly perpendicular to the expected trace, but can also be deployed in grids to cover an area. In both cases they can reveal disrupted or offset layers, low-velocity or low-stiffness layers and other signatures that indicate the position and approximate dip of a shallow fault, and help map the thickness and geometry of the cover above rock over depths of tens to a few hundreds of meters.

Resolution decreases with depth and spacing, and the inverse problem is non-unique: different subsurface models can fit the same data. Geophysical interpretations, therefore, give a family of plausible structures rather than a single sharp boundary for the shear band, and are usually refined and checked against boreholes or trenches. They rarely provide clear displacement metrics. Offsets and warping of reflectors can suggest cumulative vertical or lateral separation, but single-event slip and displacement probabilities are not resolved. In practice, geophysical methods are most effective as a way to extend the sparse control from boreholes and trenches into the space between them, improving the picture of shallow fault geometry and cover structure, rather than as a stand-alone tool for mapping fault rupture hazard.

Probabilistic fault-displacement hazard analysis (PFDHA)

PFDHA is essentially PSHA with displacement instead of ground motion as the hazard. It combines an occurrence model for surface-rupturing earthquakes on the relevant fault segment with statistical relations that give the probability distribution of displacement as a function of magnitude and distance from the mapped trace. The result is a hazard curve. For a site at a given position relative to the fault, it estimates the annual probability that displacement will exceed a given value, or the range of displacement associated with a chosen return period. PFDHA is typically applied to one mapped fault or strand at a time and uses displacement-prediction models derived from surface-rupture datasets generated by the other methods described above. It translates the mapped trace and its uncertainties into probabilistic displacement metrics that can be used in performance-based design of critical infrastructure. It does not, by itself, refine the underlying fault geometry or add new geological information. Recent work on lifeline fault crossings has proposed simplified, engineering-oriented PFDHA formulations that sit between crude empirical scaling and full site-specific analysis and are intended for Eurocode-style design use (Melissianos et al., 2023).

Assessment

Taken together, these methods rarely answer all five questions from the start of this section on their own. Desktop and remote-sensing studies are efficient at regional screening and locating candidate traces; field visits anchor these interpretations at the scale of individual buildings. Trenches and boreholes provide local cross-sections of the faulting zone and cover, but only along a few sections, while geophysical surveys interpolate structure between them over depths of roughly a few tens to a few hundreds of meters. PFDHA then combines the mapped geometry and observed or inferred displacements into probabilistic displacement metrics for design. In practice, fault-rupture investigations therefore rely on combinations of methods chosen according to project importance, site conditions and regulatory requirements, rather than on any single “best” tool.

3.3 REGULATORY DEMAND FOR SITE-SPECIFIC FAULT-RUPTURE INVESTIGATIONS

The previous sections treated fault-rupture investigations as an engineering ideal: if displacement-compatible design is the goal, then in principle an investigation would aim to answer the four questions in Section 3.1. It would locate active strands and distinguish hanging wall from footwall, describe the width and shape of the shear band, quantify expected displacement and its direction, and define the structure of the faulting zone and cover above rock. In practice, however, the scope of investigations is largely controlled by what planning and design regulations actually demand.

Most national building codes still treat surface-fault rupture, if at all, as a planning constraint rather than an explicit design action. Where active faults are mentioned, the emphasis is often on avoiding construction directly on a mapped trace, or on recognizing special "fault zones" in land-use planning, while the technical sections of the code focus on shaking hazard and generic geotechnical requirements. Only a small number of jurisdictions have issued specific guidance on how to investigate an active fault at a building site, and even fewer link those investigations clearly to the four information needs identified in this chapter.

To understand how far existing frameworks go, and where they stop, a review was made of official codes and guidelines in the countries discussed in Chapter 2, supplemented by several additional jurisdictions. For each, the analysis asks whether regulations or formal guidance actually require or describe site investigations that address, even indirectly, the four key questions:

- Fault location and setback
- width and shape of the shear band
- displacement metrics and directionality
- fault-zone and cover structure

The results are summarized in Table 3.X. In the following sections, these patterns are described for selected jurisdictions, and the table is used to highlight common gaps where current regulations do not yet support the type of displacement-based investigations that would be most useful for design.

3.3.1 Fault location and setback

In Israel, SI 413 defines a "zone of active faulting" as a belt about 200 to 30 m wide around an active or potentially active fault trace, depending on the rock depth. The standard does not prescribe particular tools but the National Geological Survey fault maps (desktop study) are mandatory to abide by. Surveyors use boreholes and shallow geophysics to show shallow rock and refine the position of the trace, but this toolkit is professional practice rather than required codified procedure.

In California, the Alquist–Priolo Act requires cities and counties to obtain a geological report before approving most new structures for human occupancy within a mapped Earthquake Fault Zone. The structure is not allowed within 50 feet of the identified active fault. Regulations require an "appropriate geologic investigation", not specific named methods, but the California Geological Survey's Special Publication 42 functions as official guidance, recommending desktop compilation of existing maps and air photos, detailed geomorphic mapping, trenching, borings and other subsurface work where needed to locate active strands at meter scale.

In New Zealand, districts that adopt the Ministry for the Environment guideline Planning for Development of Land on or Close to Active Faults, create a de facto requirement to know whether a site is inside or outside a mapped fault corridor, but the guideline does not mandate specific tools. It encourages "fault trace studies" where traces are poorly constrained and notes that trenching and detailed geomorphic mapping are often needed.

In Taiwan, within a Geologically sensitive area, any construction project must undergo a geological investigation and safety evaluation before use is approved. The law therefore makes it mandatory to address proximity to the mapped active fault, but it does not list particular methods. Central Geological Survey active-fault mapping and technical reports show the use of detailed geomorphic analysis, seismic data and drilling to delineate the "Active Fault Geologically Sensitive Area", and these effectively act as official but non-binding examples of how to carry out the required investigations.

In China, the General Code for Engineering Investigation GB 55017-2021 contains a specific clause on active faults, stating that the investigation of active faults shall determine the location, scale and width of the faulting zone, its active age, activity rate and dislocation mode, and evaluate the hazard and avoidance or mitigation measures. Where an active fault is relevant to a project, it is therefore mandatory for the site investigation to address its geometry. The code does not list particular tools, but practice begins with the national active-fault database and regional maps and then uses geological mapping, boreholes, geophysics and, in some cases, trenching to satisfy the content requirements.

In Italy, the Land Use Guidelines for Areas Affected by Active and Capable Faults are part of the national seismic microzonation framework. They are addressed mainly to regions and municipalities, not to individual projects. The guidelines of this framework require the faults and associated deformation to be mapped at a scale of at least 1:5,000. The guidelines describe the use of geological and geomorphic mapping, subsurface investigations and, where necessary, palaoseismic trenching to meet the requirement to locate the fault accurately at planning scale.

Across these examples, only a subset of jurisdictions make fault location an explicit regulatory target at the site scale. California and Taiwan require a geological investigation whenever development falls inside a mapped fault zone. In China, the demand goes further by embedding active-fault geometry directly into the general geotechnical investigation code, so that fault location and width become part of the standard scope where relevant. Italy places the strongest demand at the microzonation level, specifying the scale and accuracy of the survey. In all cases, desktop use of national fault maps is the only universally implied tool, while the more detailed methods in the investigation catalogue remain customary.

3.3.2 Displacement metrics and directionality

For design, engineers would ideally like each site investigation to deliver at least rough ranges of vertical and horizontal offset in a characteristic event, and, where possible, displacement as a function of probability. Existing regulations and formal guidance almost never ask for this explicitly. In most jurisdictions, surface-faulting is treated as a geometric siting problem rather than as a quantified displacement demand.

Among the countries reviewed, only China and Italy formally ask investigations to provide parameters that are directly related to slip size and direction. The Chinese General Code for Engineering Investigation requires that where active faults are relevant, the investigation must determine the activity rate and dislocation mode of the fault. Activity rate is essentially slip rate and dislocation mode is the sense of movement, so displacement magnitude and direction are part of the standard scope when an active fault is present. The code does not go on to translate these into design offsets for structures, but it does at least require that the underlying metrics exist in the investigation report.

In Italy, the seismic microzonation framework and the land-use guidelines for areas affected by active and capable faults require that microzonation studies report characteristic parameters of each fault, including maximum expected dislocation, fault type and recurrence characteristics. This information is used to justify and classify respect and susceptibility zones around the fault. Since this is done in the reginal level it does not directly imply on a single project location so it can not directly be used as a demand.

Formal guidance in New Zealand recognizes displacement and slip direction but does not turn them into required design numbers. The planning guideline Planning for Development of Land on or Close to Active Faults classifies faults by return period and complexity and uses examples of meter-scale offsets to illustrate the hazard, while the national active-fault datasets include attributes such as displacement and sense of movement.

In California, fault investigation guidance explains typical magnitudes of surface offset and encourages paleoseismic trenching that naturally yields per-event displacement and slip sense. This information appears in investigation reports and technical documents, and is used to justify zoning and setbacks inside Earthquake Fault Zones. It is not, however, converted into required displacement–probability relationship or deterministic vertical and horizontal design offsets for structures.

In Taiwan, Central Geological Survey active-fault reports routinely provide slip rates and classify faults by kinematics based on trenching and geomorphic evidence from events such as the 1999 Chi–Chi earthquake. These parameters are used to delineate Geologically Sensitive Areas and to justify development controls within them.

Overall, formal documents do acknowledge that surface ruptures produce meter-scale vertical and horizontal offsets and sometimes require slip rate, dislocation mode or maximum offset to be documented for planning studies. They almost never ask site investigations for ordinary buildings to convert this information into quantified displacement demands or directional design values, so the metrics needed for displacement-compatible design still come mainly from project-specific analyses rather than from codes or official guidance.

3.3.3 Width and shape of the shear band

For design, the useful quantity is how displacement falls off with distance from the primary rupture. Ordinary building regulations and planning documents almost never ask investigations to analyze that relationship. Where avoidance is chosen, widths are chosen as simple safety corridors and are not tied to any formal displacement–distance model, so they are not discussed further here.

Two national frameworks draw most directly on work about how distributed rupture is spread away from the main trace.

In Italy, the land-use guidelines for areas affected by active and capable faults, within the seismic microzonation system, require microzonation teams to define a narrow "respect zone" that straddles the primary rupture and a wider "susceptibility zone" where secondary ruptures and folding can occur. The widths and hanging-wall / footwall asymmetry of these zones are based on empirical studies of surface ruptures, such as Boncio et al. (2018), which compiled distances of distributed ruptures from the main thrust fault and fitted continuous probability density functions for rupture occurrence with distance on each side. The guideline itself does not ask site investigations to reconstruct a local displacement-distance curve, but it does embed the idea that most distributed ruptures fall within a limited distance of the main trace and that this distance depends on fault type.

In China, the general engineering investigation code already requires that active-fault investigations determine the "scale and width" of the faulting zone, and recent formal technical papers on active-fault avoidance and buffer zones go further by proposing minimum avoidance distances on the hanging wall and footwall based on global datasets of distributed ruptures. He et al. (2022), for example, argue that principal displacement is concentrated within about 100 m of the mapped fault and that distributed fault displacement decreases approximately exponentially with distance, and use this to define asymmetric avoidance and buffer zones around mapped fault traces. These recommendations are not yet hard code text, but they are formal, peer-reviewed guidance that tie corridor width to an explicit displacement–distance model.

Outside these planning-scale frameworks, the only truly explicit treatments of displacement versus distance come from critical-facility guidance rather than ordinary building codes. The IAEA Specific Safety Guide on seismic hazards for nuclear installations (SSG-9 and its updates) requires the potential for surface-fault displacement to be evaluated at candidate sites and recommends the use of PFDHA, which is built around empirical models of displacement as a function of magnitude and distance from the fault. PFDHA methodologies developed under IAEA and national regulators use global surface-rupture catalogues to derive attenuation functions for both principal and distributed displacement with distance from the mapped trace. These documents provide a formal recipe for examining the displacement–distance relationship, but they are written for nuclear plants and other high-risk facilities, not for general buildings , and they do not prescribe specific field methods beyond the usual toolbox of mapping, trenching and paleoseismic catalogues.

In summary, none of the ordinary building or planning regulations in the twelve countries reviewed tell a geologist or engineer how to investigate the way displacement decays across a site. Italy's and China's fault-zone guidelines implicitly use empirical displacement to distance relationships to set zone widths, and nuclear guidance codifies full probabilistic methods.

3.3.4 Fault-zone and cover structure

Most geotechnical codes already require boreholes, sampling and, for important structures, shear-wave velocity profiles. Stratigraphy and depth to rock are therefore characterized on almost every significant project, whether or not an active fault is present. What is unusual near faults is not that these data are collected, but that in a few cases regulations make them part of the fault-rupture decision.

In Israel, SI 413 is one of the few examples where cover thickness directly controls the legal fault corridor. The "zone of active faulting" is about 100 m wide on soft soil but shrinks to about 15 m where foundations can be placed on, or very close to, rock. As a result, projects near mapped faults routinely extend the standard borehole and shallow-geophysics program specifically to prove shallow rock and move a site from the wide soil corridor into the narrow rock corridor. The tools are ordinary, but the way their results are used is specific to the fault problem.

The draft Eurocode 8 Part 5 proposal is special in a different way. Its clause on potentially active faults makes the ability to build near a trace depend on a geotechnical parameter Hcov: the thickness of soft cover above the fault, combined with the average shear-wave velocity in that cover. Only when Hcov is large enough, for the local Vs 30 and hazard class, may continuous foundations be used near a potentially active fault; otherwise, construction close to the trace is not permitted. In many routine projects, foundation design could be satisfied by investigating only the upper few layers, so these provisions may require deeper exploration than is normally carried out in order to prove or disprove a sufficiently large Hcov. This is the only major building standard that turns the intuitive "thick soft cover diffuses rupture" idea into an explicit input parameter that decides whether fault-adjacent construction is allowed.

These two examples are closely related. Israel largely follows European structural practice, and its distinction between "soft cover" and "shallow rock" in defining active-fault corridors anticipates, in a simple way, the more explicit Hcov and Vsthresholds in the emerging Eurocode provisions. In both cases, fault-zone and cover structure move from being passive background conditions to explicit controls on whether displacement-compatible foundations can be used near a potentially active fault, and on how deep site investigations must go to demonstrate that.

Across all four information needs, regulations and formal guidance rarely go beyond broad statements of intent. They increasingly acknowledge that design should know where the fault is, roughly how large and in what direction offsets may be, how deformation is distributed across a corridor, and how the faulting zone interacts with the soil and rock cover. Each of these parameters appears somewhere in codes, microzonation guidelines or critical-facility documents, so the four questions in Section 3.1 are aligned with what regulators regard as relevant.

What is generally missing is practical direction on how to obtain this information for ordinary projects. With a few exceptions, regulations do not specify which investigation tools should be used to answer each question, what level of precision is reasonable at building or infrastructure scale, or how uncertainties should be reported and carried into design. Outside the specialized nuclear and large-infrastructure guidance, engineers and geologists are effectively left to assemble their own investigation strategies from the toolbox in Section 3.2 and to judge, case by case, whether the resulting description of fault location, displacement, deformation width and cover structure is adequate for displacement-compatible design.

3.4 PROJECT-DRIVEN INVESTIGATION ADD-ONS

For ordinary buildings, national regulations rarely go beyond very general statements that faults should be "identified" and sites "investigated". In practice, much more specific and demanding procedures appear only in projects where the consequences of failure are high. Owners and regulators then add fault-specific requirements on top of standard geotechnical investigations. The examples below show how this looks in different sectors of the construction industry.

3.4.1 Transport system structures – Caltrans

On the California state highway system, Caltrans require a surface-fault rupture displacement hazard analysis whenever a transportation project would place a structure within an Alquist–Priolo Earthquake Fault Zone or within about 300 m (1,000 ft) of a Holocene or Holocene-Latest Pleistocene fault. The requirement applies to bridges, tunnels, buried reinforced-concrete boxes and buildings associated with the project, not just bridge decks.

The analysis Caltrans require follows California Geological Survey Note 49 and Caltrans' own geotechnical guidance. It begins with desktop compilation of regional fault maps, trench records and aerial or LiDAR imagery, followed by site investigation and detailed geomorphic mapping. Where needed, trenches are excavated across suspected traces near the structure, and boreholes, CPT and shallow geophysics are used to confirm subsurface geometry. Although no numerical tolerance is specified, the combination of trenching directly at the crossing and the mapping scales recommended in Note 49 typically constrains the active strand to a corridor of only a few metres relative to the structure footprint. The study then estimates both deterministic and probabilistic fault displacements using standard empirical relations, with Caltrans spreadsheets implementing a PFDHA-type calculation for a specified probability of exceedance over the design life. The results and their uncertainties are documented in the geotechnical report and fed directly into structural analysis as imposed ground offsets.

Compared with an ordinary bridge or tunnel project, the demanded criteria do not introduce new tools, but require fault focused use of mapping, trenching and subsurface work, and a formal step where fault displacement is treated as a design load rather than an informal comment.

3.4.2 High-speed rail – California HSR

The California High-Speed Rail Authority applies a similar logic along a continuous corridor. Where the alignment crosses or closely approaches an active or potentially active fault, a dedicated fault-hazard study is required. This uses corridor-scale geomorphic mapping (often including LiDAR), trenching at critical crossings, and targeted boreholes and geophysics to locate the fault at track level and understand its recent activity.

The analysis then assigns design displacements to each crossing, typically combining deterministic estimates (for characteristic events on the fault) with probabilistic assessments. Guidance also distinguishes between a narrow primary rupture zone beneath the alignment and a broader shear belt of potential deformation that may affect earthworks, retaining structures and nearby facilities. In effect, the standard railway geotechnical toolkit is concentrated at fault crossings, and explicit permanent displacements are defined there for both structural safety and operational performance, as in performance-based design.

3.4.3 Pipelines and other linear lifelines

Guidelines for major buried lifelines, such as the American Lifelines Alliance (ALA) seismic guidelines for water pipelines, treat surface-fault rupture as one of the most severe hazards. Routes are checked systematically against active and potentially active faults, and each crossing of such a fault is treated as a special design location.

Additional investigations at crossings typically include focused geomorphic mapping, trenching or test pits across the trace and localized boreholes or cone penetration tests to define soil conditions. On the analysis side, the guidelines call for a “design fault movement” to be assigned at each crossing, scaled according to the importance class of the pipeline, and recent work increasingly uses simplified PFDHA procedures to derive these movements from empirical displacement datasets, for example the structure-independent PFDHA formulation for lifeline–fault crossings developed by Melissianos et al. (2023) and its Eurocode-oriented presentation in the Hydra workshop by Melissianos & Karaferis (2023). The pipe is then analysed over a finite length spanning the crossing, using soil–pipe interaction models to check whether the system can tolerate the imposed offset without loss of function.

3.4.4 Dams

For large dams, fault rupture is mainly a siting and concept-selection issue. ICOLD bulletins and national dam-safety regulations require special tectonic investigations where a potentially active fault may pass beneath or immediately adjacent to a proposed dam site. These studies add detailed geological mapping focused on fault traces, trenching across suspected areas, and closer spacing of boreholes and geophysical lines across the dam axis. Since the outcome is usually used to decide whether the site is acceptable at all, the focus is on the status of activity rather than estimating its potential displacement.

3.4.5 Nuclear installations

Nuclear installations sit at the most formal and conservative end of current practice. IAEA safety guides and national standards such as ANSI/ANS-2.30 require detailed characterization of capable faults in the site region and, where necessary, explicit evaluation of surface-fault displacement hazard.

Investigations typically combine multiple palaoseismic trenches, extensive borehole programs, high-resolution geophysics and comprehensive compilation of regional rupture histories. On top of that field work, PFDHA is carried out to derive hazard curves for both principal and distributed displacement at the site, at very low annual probabilities comparable to those used for nuclear ground-motion hazard. Empirical models of displacement as a function of magnitude and distance from the fault are used, so that both on-fault offsets and the likelihood of distributed rupture within the facility footprint can be estimated. These results feed directly into siting decisions (whether the site is acceptable at all) and into the design of safety-related structures and systems.

3.4.6 Relation to the four information needs

Across these sectors, the extra investigations are all built from the same tools catalogued in Section 3.2. What changes with consequence is how hard these tools are pushed and how tightly their outputs are tied to design.

- Fault location and sense of offset.

Caltrans, high-speed rail and pipeline guidelines all require site-specific fault mapping at the crossing, often including trenching, so that the active strand and its slip sense are known at the scale of the structure rather than only from regional maps. Dams and nuclear installations go further by resolving fault geometry in three dimensions beneath foundations.

- Displacement metrics and directionality.

Caltrans, high-speed rail and pipeline guidance each require explicit fault displacements to be assigned for design, and in some cases use PFDHA-type procedures to derive them. Nuclear standards make this fully probabilistic, with hazard curves for principal and distributed displacement at very low annual probabilities.

- Width and shape of the shear band.

High-speed rail guidance distinguishes between a narrow primary rupture zone and a broader belt of secondary deformation, while nuclear PFDHA explicitly models distributed displacement as a function of distance from the main trace.

- Fault-zone and cover structure.

In all sectors, fault-related studies sit on top of already substantial foundation investigations, so stratigraphy and depth to rock are normally well characterised. Only in a few cases, such as nuclear siting and some dam projects, is this information explicitly linked to decisions about whether rupture can be tolerated beneath a structure or whether a site or layout must be rejected.

In that sense, these project-driven frameworks show that the four information needs set out in Section 3.1 are not theoretical. They are the quantities that owners require once the stakes are high enough. The difference is that for ordinary buildings and infrastructure, there is still no standard way to decide how far along should an individual project go.

3.5 RECOMMENDED LEVELS OF INVESTIGATION

The review in this chapter shows that the same basic information is needed for displacement-compatible design in all settings. The catalogue in Section 3.2 shows how these can be obtained in principle, while Sections 3.3 and 3.4 show that for ordinary structures there is no clear guidance on survey goals and execution.

This section suggests a simple, consequence-based scheme with four investigation levels. It is not a code proposal, but a way to organise decisions about what information is realistically needed – and justified – for a given project.

Level 0 – No specific fault investigation

Level 0 corresponds to structures with negligible occupancy and low exposure, such as small storage buildings, agricultural sheds or greenhouses, which several jurisdictions already exempt from fault-rupture controls in planning decisions as elaborated on chapter 2. For such cases, no specific investigation of surface-fault rupture is recommended beyond whatever screening is applied at the land-use stage.

In practical terms, this level assumes that regional planning has already located known active faults, or that the risk to these low-consequence structures is tolerated.

Level 1 – Screening and layout optimisation near mapped faults

Level 1 applies to small to moderate importance buildings and infrastructure that lie near, but not obviously across, mapped or suspected active faults. The aim is to support siting and layout rather than detailed displacement design.

At this level the key outputs are:

i) Fault location and sense of offset. The project should establish whether the site lies on the hanging wall, footwall or outside a plausible fault corridor, and identify any clear surface expressions that can be avoided. The location is constrained at site scale.
ii) Fault-zone and cover structure. The basic thickness and character of the near-surface cover are identified, enough to judge whether foundations are likely to interact with shallow rock or thick soft deposits, in the spirit of the cover-thickness concept in draft EC8 to judge the likelihood of large concentrated shear versus wide spread plastic deformation.

Displacement magnitudes, directionality and shear band width are taken from regional data and generic relations, not from site-specific measurements. At this level the investigation relies on tools that do not require significant equipment or laboratory work:

- desktop studies of fault maps, aerial and satellite imagery and existing reports.
- systematic site walkover and geomorphic mapping at the plot scale.
- using information from the standard foundation investigation, if one is carried out, with possibly adding special boreholes only for fault traces.

The main purpose is to modify the layout, alignment and foundation concept so that, where possible, the building footprint and most sensitive elements are kept away from the most likely fault positions and from zones where cover conditions favor sharply localized rupture. Later chapters emphasize on the importance of orientation of structures and infrastructures with the direction of the fault.

Level 2 – Detailed site investigation for over-fault construction

Level 2 is aimed at more important buildings and infrastructure located close to mapped active faults or crossing over it, including ordinary bridges, significant public buildings or lifelines where the alignment cannot reasonably avoid the fault vicinity, and any high occupancy project. Here, a project-specific fault investigation is justified to provide inputs for displacement-compatible design.

At this level the investigation should:

i) Refine fault location and offset sense at the scale of the structure, typically to a corridor of a few metres, using targeted trenching or closely spaced boreholes, supported by detailed mapping and, when helpful, shallow geophysics.

ii) Estimate displacement metrics and directionality for a representative surface-rupturing earthquake on the fault, using empirical magnitude–displacement relations and available paleoseismic information. Where possible, displacement should be framed in probabilistic terms, for example by reporting a range with an associated return period or approximate exceedance probability.

iii) Define shear band qualitatively, distinguishing a narrow zone where large offsets are expected from a broader belt of secondary cracking and warping, informed by mapping and comparison with similar faults.

iv) Use existing foundation investigations to describe the main stratigraphy and depth to rock beneath the structure, but without requiring the much deeper and wider campaigns typical of critical-facility practice.

Tools at this level are a subset of the full catalogue: enhanced desktop studies, systematic geomorphic mapping, one or more paleoseismic trenches where access and safety allow, additional boreholes aligned with the suspected trace, and simple probabilistic or scenario-based displacement analysis. The outcome is a set of site-specific yet still conservative inputs for design, rather than a full formal PFDHA.

Level 3 – Critical facilities and unavoidable fault crossings

Level 3 is reserved for the most important and sensitive facilities, such as nuclear installations, major dams, strategic lifelines and high-speed rail crossings where interaction with an active fault cannot be avoided. In these cases, the logical ideal is that all available investigation tools are mandated and that fault rupture is treated explicitly as a design hazard.

At the same time, there is a paradox. For truly critical facilities the preferred strategy is still avoidance. Wherever siting flexibility exists, it is more rational to select sites and alignments that do not cross capable faults at all, rather than rely on detailed mitigation of large surface displacements. Level 3 investigations should therefore be triggered only where a fault crossing is genuinely unavoidable or when safety justification is required for an existing facility.

Where Level 3 applies, the investigation should aim to characterize all four information needs in as much detail as reasonably achievable:

i) Fault location and sense of offset are mapped in three dimensions, using multiple trenches, dense borehole arrays and geophysics to trace the fault through the foundation volume.
ii) Displacement metrics and directionality are quantified through PFDHA, providing hazard curves for principal and distributed displacement at low annual probabilities, with explicit vertical and horizontal components for design.
iii) Width and shape of the shear band are described using numerical models of displacement versus distance, combined with site data to estimate the likelihood and pattern of distributed rupture across the facility footprint.
iv) Fault-zone and cover structure are investigated to depths and extents comparable to those used for nuclear and major dam foundations, so that the interaction between the faulting zone and the engineered foundation system can be analyzed directly.

In practice this level involves the full set of methods, to their highest precision and formal probabilistic analysis of fault displacement. It is only justified where the consequences of failure are extreme and the project cannot practically be moved away from the active fault.

These four levels link the information needs in Section 3.1 with the investigation tools in Section 3.2 and the uneven regulatory landscape described in Sections 3.3. They provide a simple structure for deciding, project by project, how much fault-specific investigation is warranted, and for making explicit what information about fault location, displacement, shear band width and subsurface structure can reasonably be assumed at the design stage.

4. Engineering Prospects for Faulting Zone Construction

4.1 DESIGN PHILOSOPHY FOR SURFACE-FAULT RUPTURE CONSTRUCTION

4.1.1 Background

Surface-fault rupture is a PGD hazard in which relative displacement accumulates across an active fault and reaches the ground surface. Unlike seismic shaking, which is commonly represented for design as inertia-related actions, the governing demand for structures and infrastructure near an active fault is a permanent displacement field that may include vertical offset, horizontal offset, and distributed strain and curvature within a finite shear band. The practical implication is that a project located over or near an active fault is framed primarily as a compatibility problem between an engineered system and a ground surface that may not remain continuous, level, or uniformly deforming after a faulting event. This framing is consistent with both field evidence and controlled modelling studies of surface rupture interacting with built assets and near-surface soils (Bransby et al., 2008).

Chapter 3 established that the feasibility of any rupture-mitigation strategy depends strongly on what can be constrained at the site scale. These include fault location and sense of offset, displacement metrics and directionality, the width and distribution of the shear band deformation field, and the fault-zone and cover structure. These inputs are not merely descriptive. They determine whether a project can credibly adopt a displacement-compatible design strategy or whether it would be better to avoid the risk of surface rupture.

Force-based seismic design relies on limiting inertial demands through ductility and dynamic response that depends on a system's mass, stiffness, and damping. Surface-fault rupture does not primarily impose an inertial demand. It imposes differential PGD that remains after the event and therefore does not diminish simply because the system is lighter, more flexible, or more damped. Once a permanent offset occurs, the governing question is not whether member forces exceed strength at one instant, but whether the system remains stable or functional while its geometry and boundary conditions are permanently altered.

A clear illustration is provided by buried lifelines. In pipeline fault-crossing design, rupture is treated as a prescribed PGD pattern applied to the pipe–soil system, and performance is verified using strain- and curvature-based acceptance criteria rather than a force-controlled check (O'Rourke & Wang, 1977). Where probabilistic fault displacement hazard analysis is used, the approach remains displacement-driven: displacement is quantified by exceedance level and then mapped to performance states through nonlinear soil–pipe interaction response (Youngs et al., 2003).

4.1.2 Performance objectives

Performance objectives are stated explicitly because surface-fault rupture is displacement-driven and different assets tolerate different outcomes. Ordinary buildings are typically governed by life-safety and stability, so permanent tilt, settlement, and major repair can be acceptable provided gravity-load paths remain reliable (Pitilakis & Tsinidis, 2014). Lifelines and transport corridors are often governed by containment, operability, and recovery, because localized failure can produce system-scale consequences (ALA, 2005).

Design criteria are derived from the combination of the required performance and the achievable precision in defining rupture location, shear band width, and displacement directionality. Strategies that aim on localizing deformation in a specific segment, such as sacrificial zones, benefit strongly from tighter spatial constraints. Otherwise, the sacrificial concept tends to expand into wider buffered corridors and recovery planning. In contrast, rigid-body tolerance can be more forgiving of site-scale uncertainty, since coherent rotation and load redistribution do not require a single predetermined shear line (Bransby et al., 2008). Displacement-compatible detailing for pipelines remains explicitly displacement-driven, with performance verified through strain/curvature acceptance rather than force-controlled checks (O'Rourke & Wang, 1977; ALA, 2005).

4.1.3 Three response concepts

Concept A: Rigid-body mechanism tolerance

Rigid-body tolerance describes systems that remain stable by behaving as a coherent block under imposed ground deformation. For shallow-founded ordinary structures, continuous raft and box foundations can bridge localized loss of support, redistribute bearing pressures, and rotate in a controlled manner. A key benefit for the superstructure is that a stiff, continuous foundation tends to smooth short-wavelength ground distortion, reducing differential support movements transmitted into the superstructure even when overall rotation increases (Anastasopoulos et al., 2008a). Experimental centrifuge studies and numerical simulations indicate that this mechanism can preserve global stability even when local cracking and permanent rotation occur (Bransby et al., 2008).

This concept is comparatively tolerant of epistemic uncertainty in rupture location within a site-scale envelope. First, the foundation response can accommodate a range of rupture emergence locations because rotation and bearing redistribution are not tied to a single predetermined shear plane. Second, stiff foundations may alter near-surface deformation patterns, including bifurcation and diversion of rupture beneath the footprint, which can reduce localized distortion demands relative to a free-field trace (Kelson et al., 2001; Anastasopoulos et al., 2008b). Consequently, rigid-body tolerance can remain viable when the fault trace is constrained only to a corridor rather than pinpointed, although the acceptable outcomes typically include serviceability loss due to permanent tilt and settlement (Bransby et al., 2008).

Concept B: Sacrificial deformation zones and rapid repairability

Sacrificial design formalizes the idea that deformation will occur and assigns it to a deliberate zone where damage is acceptable, inspectable, and repairable. The central design variable is geometric: the zone's location, width, and length must be compatible with the expected rupture band and with residual uncertainty. Complementarily, uncertainty can be managed within the asset through a weak-link hierarchy: the sacrificial segment is detailed to be more deformable (lower stiffness/strength, replaceable components, and a controlled failure mode), while adjacent components are provided with sufficient overstrength so that deformation and damage localize preferentially within the intended repairable mechanism, consistent with capacity-design logic (Paulay & Priestley, 1992). This hierarchy does not pull the ground rupture to a chosen line, but it can help ensure that if significant distortion is imposed within the crossing corridor, the system response concentrates into the intended mechanism rather than into critical connections or brittle components.

This concept is more sensitive to site-scale precision than rigid-body tolerance. If a sacrificial zone is intended to protect critical components by concentrating deformation in a specified segment, the design must be confident that the dominant shear and distortion will occur within that segment, or else the zone must be widened to bracket plausible deformation locations. Where confidence is limited, sacrificial strategies typically expand into buffered corridors and recovery-focused provisions, including geometric allowance for post-event realignment so operational geometry can be restored after repair.

This logic is visible in highway corridor practice, where fault-affected road sections are often reopened through temporary grading, ramping, pavement repairs, and local realignment within the right-of-way, accepting short-term loss of serviceability but targeting rapid restoration. Following the 2016 Kaikōura earthquake in New Zealand, for example, surface rupture and related ground deformation contributed to road closures, yet access at several locations was reinstated using temporary ramping/repairs and by adjusting alignments during the recovery program (Robinson, 2018). Within this thesis, roads are treated as the clearest example of a surface-laid corridor where sacrificial and recovery-focused strategies are structurally natural.

Concept C: Displacement-compatible detailing

Displacement-compatible detailing aims to maintain stability and functionality under imposed fault offset by accommodating deformation. In practice this is achieved through ductile demand paths and built-in degrees of freedom, such as segmented layouts, jointed connections, controlled sliding interfaces, and flexible components that tolerate rotation, extension, and curvature without loss of integrity (O'Rourke & Liu, 1999). This concept is particularly relevant for buried infrastructure, where inspection and repair after faulting can be slow, expensive, or impractical. The preferred outcome is therefore often continued containment and service with limited or no damage, rather than a repairable sacrificial failure mechanism (ALA, 2005).

Compared with rigid-body tolerance and sacrificial zoning, displacement-compatible solutions typically rely more strongly on defining the demand, not only displacement magnitude but also directionality, crossing geometry, and deformation distribution. That is because performance is governed by strain and curvature limits and joint capacities under prescribed ground movement. Within this category, some devices are specifically intended to concentrate deformation while developing minimal resistance forces, for example low-friction sliding interfaces or purpose-designed couplings that allow relative movement to occur with limited force transfer to adjacent components (ALA, 2005).

4.1.4 Scope of Chapter 4

The scope of Chapter 4 was defined by first surveying the range of assets that may intersect a surface-fault rupture hazard, and then selecting exemplars that collectively represent the three response concepts introduced in this chapter.

Classes considered:

A. Structures - Structures represent the highest exposure and the most common design case. In contrast to distributed networks, individual structures occupy a limited footprint and can be configured to behave in a coherent manner that reduces differential support movements transmitted into the superstructure.

B. Infrastructure

Infrastructure systems were subdivided into four categories based on embedment condition and the dominant soil–structure interaction mechanisms under imposed fault displacement.

i) Underground infrastructure:
  - Pipelines.
  - Tunnels.
  - Cut-and-cover systems and trenches

These systems are strongly governed by soil–structure interaction and are often difficult to inspect and repair immediately after faulting, which tends to favor deformation accommodation and continuity-based design strategies.

ii) Surface-laid infrastructure
  - Railways.
  - Roads and highways.

These systems often lose service through misalignment and loss of operability rather than structural collapse, and mitigation commonly combines a defined crossing corridor with repair- and recovery-focused provisions.

iii) Retaining and earth-support systems

Retaining systems are sensitive to local ground conditions and large permanent deformation modes, with multiple possible failure mechanisms. Their performance depends on coupled soil–structure response, since the wall both restrains and relies upon the retained ground for stability.

iv) Elevated infrastructure
  - Elevated road and rail structures
  - Above-ground racks and supported lifelines

These systems introduce additional complexity (bearings, seats, redundancy, approach transitions, and foundations) and are commonly governed by agency-specific procedures and performance-based design approaches.

Rationale for selections:

Elevated infrastructure (bridges & viaducts) - Bridges are widely recognized as critical at fault crossings and are the subject of substantial dedicated research and agency guidance. In practice, bridge projects commonly adopt performance-based, corridor-specific procedures with fault-focused investigation and explicit displacement demands. For this thesis, a full treatment of bridges was not pursued because it would expand into a separate, self-contained topic with many typology-dependent design paths and agency frameworks. Bridges are therefore noted as comparatively well covered in existing guidance and outside the primary scope of this thesis.

Retaining structures - Retaining and earth-support systems are also important at fault crossings. However, the available information is less unified. Most published guidance addresses shaking-driven retaining-wall failure modes. Comparatively few well-documented cases isolate direct surface-rupture crossing effects. Where rupture does intersect a wall, case histories show combined vertical and horizontal offsets can trigger nonstandard hybrid mechanisms (e.g. sliding, toe heave, overturning) that are difficult to generalize across typologies (Fang et al., 2003). The resulting variability limits the thesis value of a short treatment and motivates dedicated future work Performance depends strongly on wall type, geometry, soil profile, drainage, and global stability, and fault-rupture-specific design approaches are not as consistently described across common retaining systems. As a result, retaining structures are identified as a high-priority area for future focused work rather than treated superficially in this thesis.

Final selections:

From all considered classes presented, the thesis selects three that are both practically important and technically transferable. These vary from each other in codification, PGD behavior and design criteria:

- Ordinary buildings (Concept A) - Ordinary buildings represent rigid-body tolerance, where stability is achieved through coherent system response, while accepting potential serviceability loss. Rupture-specific design pathways for ordinary buildings are often limited or inconsistent in regulation, with some jurisdictions emphasizing avoidance. Buildings are selected because they combine the largest exposure with the clearest gap between hazard and routine design practice.
- Surface-laid: road corridors (Concept B) - Roads represent sacrificial and recovery-focused zoning, where deformation is managed within a defined corridor and service is restored through repair and regrading and realignment. Codification is more mixed and often project driven, or agency driven, rather than uniform. Roads are selected due to very high exposure and because they often govern emergency access and regional mobility.
- Underground: pipelines (Concept C) - Pipelines represent displacement-compatible detailing. They are comparatively well formalized in lifeline guidance through prescribed displacement demand and strain/curvature acceptance criteria. They are selected due to their network-level consequence and the limited feasibility of post-event access and repair at fault crossings.

Scope decision matrix.

The three exemples selected above are not intended to represent the full range of assets exposed to surface-fault rupture. Rather, they were chosen to (i) span the three response concepts introduced in Section 4.1, (ii) reflect different levels of fault-rupture codification in current practice, and (iii) correspond to high-exposure or high-consequence asset classes. Table X summarizes the broader set of options considered and shows how the candidate asset types align with the dominant response concepts and with codification maturity. In the table, "codification" refers specifically to fault-rupture provisions and guidance, not general seismic code coverage. "Dominant concept" denotes the primary intended mechanism at fault crossings, recognizing that some systems may require hybrid strategies.

Table 1: Scope decision matrix for Chapter 4 options.

Response concept (dominant mechanism)	Low codification / fragmented	Medium codification / mixed practice	High codification for fault-rupture/PGD
A. Rigid-body tolerance	***Ordinary buildings — Selected*** Retaining systems	—	—
B. Sacrificial + recovery zoning	Local surface corridors	***Road corridors — Selected***	Rail corridors
C. Displacement-compatible detailing	—	Tunnels Cut-and-cover trenches	***Pipelines — Selected*** Bridges/viaducts

4.1.5 Conclusion

Surface-fault rupture design is governed by PGD demand rather than transient inertial loading. The feasible design approach therefore depends on both the required performance objective and the level of site-scale constraint that can be achieved for rupture location, shear band width, and displacement directionality. Across Concepts A–C, reliance on site-scale constraint increases. Rigid-body tolerance is relatively robust to localization uncertainty, sacrificial zoning depends more on bounding deformation location/extent, and displacement-compatible detailing depends on quantified displacement magnitude and directionality. In Chapter 4, this logic is developed through three examples selected to span the response concepts introduced above: ordinary buildings to illustrate rigid-body tolerance under relatively broad uncertainty, road corridors to illustrate sacrificial and recovery-focused zoning at corridor scale, and pipelines to illustrate displacement-compatible detailing verified against strain and curvature acceptance criteria. This structure keeps the chapter focused on transferable, decision-relevant design philosophy rather than an exhaustive catalogue of asset types.

4.2 RIGID (REGULAR) STRUCTURES OVER ACTIVE FAULTS

This section develops the "rigid-body tolerance" response concept (Concept A; Chapter 4.1) for ordinary buildings and similar shallow-founded structures located near active faults. The chapter therefore focuses on how permanent surface-fault displacement interacts with relatively rigid structures' foundation systems, and how coherent foundation response can preserve global stability. The chapter therefore focuses on decision-relevant behavior, and on what can and cannot be justified given the level of site investigation described in Chapter 3. The discussion proceeds from physical mechanisms, to common foundation configurations, and then to the limits of current building-code guidance for over-fault construction.

4.2.1 Background

Surface-fault rupture presents one of the most challenging forms of PGD for structural foundations. When a tectonic rupture reaches the ground surface, it produces highly localized differential movement of the soil that conventional seismic design, which is developed primarily for transient shaking, cannot accommodate. The problem has only recently been examined systematically. Until the late 1990s, research in soil-structure interaction focused almost entirely on cyclic response, while the static offset of the fault plane was regarded as a rare geologic anomaly rather than a quantifiable design hazard. The 1999 earthquakes in Turkey and Taiwan, which ruptured beneath buildings and infrastructures, renewed attention to the subject and motivated the first coordinated experimental and analytical programs on *fault-foundation interaction* (Faccioli et al., 2008; Anastasopoulos et al., 2008a).

From the engineering viewpoint, surface rupture belongs to the wider category of PGD seismic hazards, which also includes liquefaction-induced settlement and lateral spreading (O'Rourke & Jeon, 1999; Pitilakis & Tsinidis, 2014). In this study however, PGD is regarded as seismic rupture hazard term. These processes differ from dynamic shaking by the permanence of deformation and the concentration of strain. They require a design philosophy that is displacement-controlled rather than the familiar force-based approaches, since the intensity measure is a ground offset rather than acceleration. For ordinary buildings, this framing aligns with the rigid-body tolerance approach (Concept A; Chapter 4.1): the expected response is dominated by gross foundation translation/rotation rather than distributed member ductility, and the governing objective is typically life-safety and collapse prevention, not operability. Consequently, foundations over active faults should be conceived not only to resist inertial demands but also to maintain structural integrity under imposed differential displacements. This evolution in thinking has increasingly influenced modern approaches to fault-crossing analysis (Anastasopoulos et al., 2008).

Field reconnaissance following the Kocaeli, Düzce-Bolu, and Chi-Chi earthquakes revealed that the interaction between faults and structures is not purely destructive but mechanical and reciprocal. Faccioli et al. (2008) observed that relatively heavy or stiff buildings supported by continuous raft foundations sometimes diverted the rupture, experiencing mainly rigid-body rotation rather than collapse. In contrast, lighter or flexible foundations allowed the rupture to pass through them, producing large differential settlements and structural distress. These findings suggested that the stiffness and surcharge of the foundation could influence the rupture trajectory in the foundation vicinity, and the resulting ground-surface deformation pattern (Anastasopoulos et al., 2008b).

To investigate this mechanism under controlled conditions, Bransby et al. (2008) conducted a series of geotechnical centrifuge experiments at the University of Dundee. Reverse-fault offsets were imposed in dry sand layers beneath rigid and flexible footings. The experiments demonstrated that a heavily loaded, stiff foundation could deviate the fault plane rather than allowing it to emerge directly beneath the footing. This beneficial diversion was accompanied by measurable foundation rotation, illustrating a central trade-off for ordinary buildings between rupture protection and serviceability loss (Bransby et al., 2008).

Subsequent research combined physical modelling with numerical simulation to generalize these observations and explore parameter sensitivity. Finite-element analyses using different constitutive descriptions of soil behavior were validated against centrifuge results, establishing a consistent numerical basis for studying fault–foundation interaction and for interpreting how footing stiffness, surcharge, and soil conditions influence deformation localization near the ground surface (Faccioli et al., 2008).

Parallel theoretical work by Anastasopoulos, Gerolymos, Gazetas and Bransby (2008) produced a semi-analytical framework for fault rupture in the free field, later extended to foundation interaction. The model described rupture path geometry as a function of soil friction and dilation angles and predicted the ground surface displacement profile for dip-slip faults. These expressions provided a first practical means of estimating rupture outcrop location and vertical displacement without resorting to full numerical simulation.

The integration of these experimental and analytical studies established a coherent view of the *fault–foundation system* as a coupled mechanism (Anastasopoulos et al., 2008; Bransby et al., 2008). The hazard can no longer be regarded as purely external. The structure and foundation actively influence rupture propagation. Rigid, continuous foundations can shield the superstructure by diverting the rupture, yet at the expense of larger rotations and potential serviceability loss. Flexible or lightly loaded foundations permit the rupture to pass through, reducing rotation but concentrating damage within the structure. Consequently, design objectives must balance life-safety protection with controlled deformation and reparability. At a national scale as reflected in Chapter 2, this is not merely a technical curiosity. Existing and future development near active faults makes surface-rupture performance a matter of public safety, continuity of essential services, and post-earthquake recovery capacity. Addressing it explicitly through investigation requirements, land-use controls, and realistic performance objectives, reduces disruption and accelerates recovery following major earthquakes.

4.2.2 Failure Mechanisms

When a surface-

fault rupture propagates into the foundation zone, the resulting PGD may involve either or both vertical and horizontal components. These impose complex soil-structure interactions that depend on the fault regime and the relative stiffness between the soil and the structure systems. Experimental and numerical studies have identified a consistent set of deformation mechanisms. For clarity, the following discussion separates them by displacement direction and typical fault type, while recognizing that many earthquakes produce mixed or oblique motions.

A. Vertical Displacement Mechanisms (Reverse and Normal Faulting)

i) **Uplift and bearing-capacity loss -** In reverse faulting, the hanging wall side of the foundation is driven upward as the rupture approaches the surface. Centrifuge and numerical analyses (Bransby et al., 2008) show that this upward motion causes detachment of the soil under the uplifted edge and compression of the opposite side. The result is a steep stress gradient and partial loss of contact. Field observations from Chi-Chi (1999) and Kahramanmaraş (2023) show buildings raised several decimetres on one side, consistent with these mechanisms (Chung et al., 2000; Aydan et al., 2024). The loss of bearing resistance on one edge initiates localized shearing of the raft and concrete cracking at most loaded foundation edges, while the compressed footwall edge can experience crushing or settlement as load is transferred.

ii) **Rigid-body rotation and tilt -** As uplift continues, the footing typically rotates about the footwall edge, generating rigid-body tilts of 5–10 degrees in centrifuge experiments (Bransby et al., 2008; Anastasopoulos et al., 2009). Such rotations redistribute axial forces among columns and beams, often forming plastic hinges at the raft perimeter (Gazetas & Anastasopoulos, 2008). Even when the structural frame remains intact, modest tilts can significantly affect functionality and serviceability. Acceleration-sensitive non-structural components such as ceilings, shelving, and infill partitions may detach or overturn, while rotational distortion of the foundation can stress attached service lines where they enter the structure, leading to leakage or rupture.

iii) **Local rupture bifurcation and diversion -** Under stiff or wide rafts, the fault plane may split into two branches, deflecting around the structure rather than cutting directly beneath it (Bransby et al., 2008; Loli et al., 2011). This *bifurcation* reduces direct offset under the building but intensifies deformation at its edges. Karamitros et al. (2007) and Anastasopoulos et al. (2009) observed that the diverted rupture produces concentrated shear and settlement zones along the footing boundaries. In field terms, this behavior explains why adjacent pavements or narrow annexes often show open cracks while the main structure remains largely intact (Kelson et al., 2001).

B. Horizontal Displacement Mechanisms (Strike-Slip)

i) **Differential shear and torsional distortion -** Strike-slip rupture introduces opposing horizontal movements beneath the two sides of a foundation. Finite-element simulations (Anastasopoulos et al., 2009) demonstrate that this differential shear generates torsional rotation of the superstructure about a vertical axis, particularly for asymmetric building plans. Shear stresses concentrate along one diagonal of the raft, leading to cracking or sliding at the soil–foundation interface. Observations from the 2010 Darfield earthquake show residential buildings twisted relative to their basements, consistent with such mechanisms (Van Dissen et al., 2011).

ii) **Shear-induced cracking and lateral spreading -** Where the fault offset propagates through soft or saturated deposits, lateral spreading amplifies horizontal strain. The footing experiences diagonal tension on the leading edge and compression on the trailing edge, as documented in Gazetas & Anastasopoulos (2010). Structural implications include diagonal cracking in shear walls and potential torsional coupling between floors. Following PGD, the structure's geometry changes rather than its acceleration environment. Displacement-sensitive systems such as rigid pipes, cladding and glazing, are strained or distorted by the geometry change of the superstructure.

iii) **Edge offset and connection failure -** If horizontal rupture localizes directly besides a building, sharp steps form at the contact between foundation and adjacent ground. This misalignment damages exterior stairs, pavements, and buried utilities that cross the fault. Pipe or conduit rupture at the foundation perimeter has been reported repeatedly after strike-slip events such as Chi-Chi and Kahramanmaraş (EERI, 2000; Aydan et al., 2024).

Progressive sequence of deformation: In consideration of the observation that most real ruptures include both vertical and horizontal components, the experimental, numerical, and field observations integration demonstrates that the typical progression of failure can be summarized as:

i) Approach of the rupture and distortion of the underlying soil.
ii) Uplift of the hanging wall edge with partial contact loss.
iii) Rigid-body rotation and differential shear.
iv) Impact or re-contact stresses producing cracking and settlement.
v) Structural and non-structural serviceability loss.

This progression emphasizes that failure is rarely instantaneous and that many structures pass through early stages of rotation and differential movement without collapse, yet they may become functionally unusable.

4.2.3 Codes and Guidelines

The engineering study of conventional building foundations subjected to surface-fault rupture began only in the early years of this century, following the destructive earthquakes of the 1990s (Faccioli et al., 2008; Bransby et al., 2008). Because building codes evolve slowly in nature, requiring extensive experience and professional consensus before adopting new design concepts, the formal provisions that now exist remain preliminary and not yet exhaustive. Some acknowledge the hazard but provide only broad guidance, leaving most analytical and detailing issues to professional interpretation. While linear infrastructure such as pipelines and bridges already benefits from mature, displacement-compatible manuals such as ALA 2005, comparable frameworks for conventional buildings are still emerging.

As discussed in Chapter 2, the lack of codified engineering procedures for fault-crossing foundations led several jurisdictions to adopt the simplest control measure- prohibition. Countries such as Israel, Taiwan, and Turkey introduced setback rules through their national seismic or planning codes. Those measures replaced engineering accommodation with legal exclusion, illustrating how regulation can substitute for the vacuum of design methodology.

The following discussion therefore identifies the current technical and regulatory baseline for foundations potentially affected by fault rupture, focusing on few documents that are directly or indirectly relevant:

i) The current **Eurocode 8 Part 5 (2006).**

ii) The **Draft Eurocode 8 Part 5 (2024).**

iii) The Recommended Seismic Provisions FEMA P-2082 (2020).

iv) The **Taiwan Building Technical Rules Article 262 (2010).**

Subsequent subsections examine each in detail and consider how their principles may inform the development of future design guidance for conventional structures.

4.2.3.1 *Eurocode 8 (2006) — Part 5 clause 4.1.2*

Clause **4.1.2** of **EN 1998-5:2004** is the only EC8 provision that explicitly refers to *faults* in the context of buildings and foundations. In summary it instructs that:

- Buildings of **importance shall not be erected in the immediate vicinity** of tectonic faults that are officially recognized as **potentially active** by authorities.

- Classifying a fault as **non-active.**

- **Stating that special geological investigations** are demanded for urban planning and for **important structures** near **potentially active faults**.

This clause represents a formal recognition, within a primary European building code, that surface-fault rupture constitutes a distinct hazard thus requiring explicit attention. Its provisions establish a cautious planning posture. Construction should avoid the immediate proximity of known active faults, and geological studies must be undertaken wherever the possibility of rupture exists. By linking the rule to the building importance classes, the code associates the decision on siting with structural consequence, implying that critical facilities warrant stricter investigation and avoidance criteria.

Despite its value as a policy statement, Clause 4.1.2 is brief, probably deliberately, and leaves considerable scope for interpretation. The phrase "*immediate vicinity*" is not quantified, and no National Annex to date defines a numerical setback distance. Consequently, the clause has remained declarative and its interpretation has been deferred to national or local planning regulations rather than to engineering criteria. The required "*special geological* *investigations*" are also open-ended. The clause provides no specification of the methods, scale, or performance objectives of such investigations, merely their necessity. Terminology such as "*potentially active fault*" or structures "*not critical for public safety*" invites local interpretation. More importantly, the clause stops at the level of siting and investigation. It offers no analytical framework or acceptance criteria. The practical consequence is that designers who must contend with potential fault rupture have no explicit Eurocode methodology for displacement compatible design and must rely on judgement or non-European guidance.

Cross-referencing within the Eurocode family further underscores this gap. Prescriptive rules for PGD are found only in *EN 1998-4* (clause 6.6 "Design measures for fault crossings"), but those apply exclusively to pipelines and other linear infrastructure. No comparable procedure is provided in Part 5 for conventional building foundations.

Clause 4.1.2 therefore functions primarily as a trigger for geological investigation and planning control rather than as a design aid. Its brevity and interpretability highlight the early stage of codified understanding in this field.

4.2.3.2 *Draft Eurocode 8 (2024) — Part 5: Provisions near Potentially Active Faults*

The 2024 draft of Eurocode 8 Part 5, introduces the first quantitative criteria within the European code framework for construction in the vicinity of potentially active faults. However, it is not yet legally binding, as it remains under the European Committee for Standardization to be approved, and awaits the publication of national annexes. The draft represents a conceptual shift: surface-fault rupture is now treated as a geotechnical condition that may be accommodated through design, rather than a reason for automatic exclusion.

Clause 7.1.2 "Potentially Active Seismic Faults" specifies that structures of Consequence Classes 2 and 3 (CC2 and CC3) may be constructed near an active fault trace only if two conditions are satisfied:

- the foundation is continuous and stiff, capable of redistributing loads under imposed differential displacements; and
- Hcov - the soft soil cover thickness, between the ground surface and the top of the fault exceeds the threshold derived from Figure 7.1, which expresses the minimal necessary Hcov as a function of the average shear-wave velocity (V_S) within the depth of influence of the foundation and the seismic-action classes a, b or c.

In effect, the clause is aiming at a coherent, rigid-body type response of the foundation–structure system, which is consistent with a life-safety objective rather than operability for conventional buildings.

By referencing the seismic-action class, the figure links the required soil-cover thickness both to local hazard level and to ground stiffness. The relationship reflects established experimental evidence, that is softer soils with characteristic lower V_s tend to diffuse fault rupture over a wider zone, reducing the vertical step at the surface, whereas stiffer soils with characteristic higher V_s concentrate deformation, requiring greater cover to attenuate its effect on foundations. A note clarifies that V_s should be determined using a depth equal to the influence zone of the foundation. In practice, this task falls to the geotechnical consultant, who provides V_s from site-specific geophysical testing. This requires site investigation adequate to constrain the near-surface ground model and to support the classification inputs used by the clause (Chapter 3).

The associated Consequence-Class table defines the clause's scope. Since only CC2 and CC3 are included, CC1 structures, which are minor agricultural or low-occupancy buildings, are implicitly outside its scope. It may therefore be assumed, consistent with the approach taken in the Israeli seismic code, that such low-consequence works will generally be allowed near faults without further regulation, subject to local planning approval.

Sub-clauses (3) to (6) extend the provision from siting to basic design principles. Designers of eligible structures are instructed to minimize the impact of faulting through appropriate foundation or soil measures, and to consider ground improvement where necessary. Where piles are employed for soil improvement, they must not intersect the fault plane and must terminate at least ten diameters above it. In addition, they must not be connected to the foundation structure in any way. While this rule provides a geometric safeguard against direct shear transfer, it is of limited practicality. In reverse-fault settings the rupture plane is seldom planar or predictable, and even a nominal ten-diameter clearance cannot ensure that shearing will not occur closer to the footing. Moreover, the distinction between hanging wall and footwall conditions becomes ambiguous in complex faulting zones. In practice, non-reinforced and discontinuous soil-improvement methods, such as rubble inclusions or loose granular piles, are preferable, as they modify ground stiffness without creating rigid dowels that could localize failure.

The clause briefly refers to extended linear works. Tunnels, retaining walls, or pipelines, requiring that they be sufficiently stiff or detailed to accommodate differential movement. Since these are covered elsewhere in the code and in other chapters of this thesis, no additional guidance is introduced in the 2024 draft.

Although Clause 7.1.2 represents a considerable conceptual advance over the 2006 edition, it remains qualitative and framework-level. It does not specify analytical procedures, acceptance criteria for tilt or rotation, or target displacement values, nor does it attempt to predict deformation modes as the analytical frameworks of Gazetas et al. do. The meaning of "continuous stiff foundation" is not quantified, and the mapping of seismic-action classes to ground-motion levels is deferred to national annexes. Consequently, implementation will still rely heavily on professional judgment and local interpretation.

Despite these limitations, the clause's significance is substantial. For the first time in a primary European standard, it codifies a measurable route to code-permitted accommodation under defined conditions using physically quantifiable parameters. Yet, this should be seen only as a first step. The process of codification in Europe is inherently lengthy, political and financially influential. The inclusion of a single, embryonic clause may define design practice for decades before a full methodology emerges. The present draft therefore represents both progress and caution since it makes a necessary acknowledgement of fault rupture within the Eurocode framework, but one that must be expanded through continued research and national adaptation if it is to evolve into a true design standard.

4.2.3.3 *FEMA P-2082 (2020) - Provisions within the NEHRP Framework for seismic shaking*

The FEMA P-2082-1 document, NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, constitutes the current technical foundation of seismic design in the United States. The document provides the scientific and procedural basis that state and municipal codes adopt by reference, most notably the International Building Code (IBC) and ASCE7. While FEMA P-2082 primarily addresses shaking design, it also contains the only nationally recognized clauses that explicitly reference surface-fault rupture as a geotechnical hazard to be investigated or, in many cases, avoided altogether.

Clause 11.8.1 establishes a categorical restriction against placing buildings directly over active faults in the most severe design environments:

"A structure assigned to Seismic Design Category E or F shall not be located where a known potential exists for an active fault to cause rupture of the ground surface at the structure."

This language codifies the standing American planning principle originating with California's Alquist–Priolo Earthquake Fault Zoning Act (1972). Where credible surface rupture is expected, avoidance is adopted over design. The rule applies only to the highest

Seismic Design Categories (SDC E and F), defined within the same chapter of the NEHRP Provisions.

Risk Categories and the Derivation of SDC E and F:

NEHRP first classifies buildings by Risk Category I–IV, reflecting societal consequence of failure:

Table 2. Risk Category classification by NEHRP

Risk Category	Typical structures	Reliability objective
I	Agricultural, storage, or low-occupancy buildings (greenhouses, barns, sheds)	Minimum
II	Ordinary residences and commercial buildings	Normal
III	High-occupancy or community-significant facilities	Enhanced
IV	Essential facilities, emergency centers, hazardous-material storage	Maximum

The Seismic Design Category (SDC E–F) combines this risk level with the mapped ground-motion severity, represented by spectral accelerations at long (S_1 = 1 s) periods. For most structures, the decisive parameter is S_1, the long-period spectral acceleration for the Maximum considered Earthquake (MCE_R), an event with a 2% probability of exceedance in 50 years as the file defines.

Table 3. Seismic Design Category Definition by S_{D1} by NEHRP

SDC Definition by S_{D1}	
A	$S_{D1} < 0.067g$
B	$0.067g < S_{D1} < 0.133g$ for risk categories I to III.

SDC	Definition by S_{D1}
C	$0.067g < S_{D1} < 0.133g$ for risk category IV, and $0.133g < S_{D1} < 0.2g$ for risk categories I to III.
D	$0.133g < S_{D1}$ for risk category IV, and $0.20g < S_{D1}$ for risk categories I to III.
E	Very-high hazard* ($S_1 \geq 0.75$ g) for Risk Categories I–III.
F	Very-high hazard* ($S_1 \geq 0.75$ g) but for Risk Category IV.

* The S_1 relation with SD_1 differs based on ground type since:

$$SD_1 = \frac{2}{3} * SM_1 = \frac{2}{3} * Fv * S_1$$

Accordingly, SDC E and F correspond to the same seismic activity level, distinguished only by the building's importance. The prohibition in clause 11.8.1 therefore targets all structures and infrastructures of this maximal activity level, regardless of their risk category.

Section 11.8.2 mandates a site-specific geotechnical report for buildings assigned to SDC C through F. The investigation must evaluate all relevant hazards, including:

"Surface displacement caused by faulting or seismically induced lateral spreading or lateral flow.

The report must provide recommendations for foundation design or other mitigation measures."

However, because section 11.8.1 already excludes SDC E and F sites from fault-crossing construction, this requirement is functionally relevant only to SDC C and D with respect to faulting. In these moderate-to-high hazard zones, where smaller or more deeply buried faults may produce limited deformation, construction is allowed provided that the geological study quantifies expected displacement and proposes appropriate engineering responses. The clause deliberately refrains from giving any numerical displacement limits, recognizing that fault behavior and ground conditions are highly site-dependent. In this sense, the clause reflects the investigation dependent logic proposed in Chapter 3, where increasing structural importance justifies and requires a higher level of fault characterization before fault-crossing construction can be implemented.

Commentary C11.4 — Geometry and Definition of Fault Distance

The commentary accompanying Section 11.4 discusses the difficulty of defining a near-fault site. The extent of potential deformation depends on rupture type, dip, depth, and magnitude. Figure C11.4-1 illustrates the measurement of horizontal fault distance from the site to the projected fault plane.

A steep strike-slip fault such as the San Andreas (dip ≈ 85–90°) confines the zone of surface rupture to a narrow corridor tens to a few hundreds of meters wide, whereas a low angle reverse fault such as the Sierra Madre (dip ≈ 30–40°) projects more than ten Kilometers laterally.

A simple geometric model shows that a 35°-dipping fault reaching a seismogenic depth of 10 km would intersect the surface roughly 14 km horizontally from its lower tip explaining why the zero fault distance zone in code terms can encompass wide corridors. These geometric relationships underpin FEMA's caution that the true extent of near-fault influence varies greatly and cannot be prescribed by a single setback value.

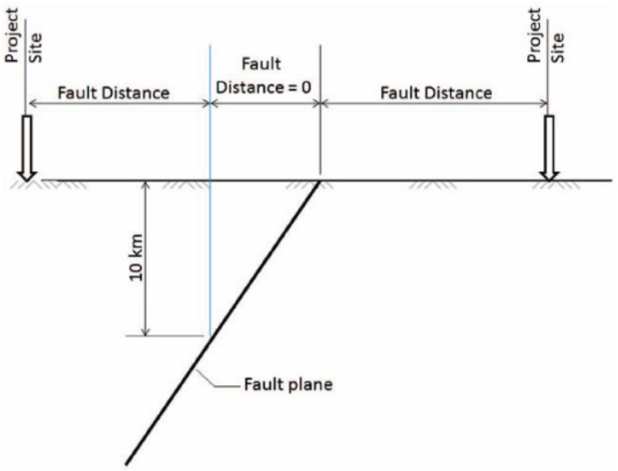

FIGURE C11.4-1 Fault Distance for Various Project Site Locations

Figure 1. Screenshot of figure C11.4-1 Fault distance for various project site location from NHERP

Assessment:

The restrictions introduced by FEMA P-2082 on construction across active faults echo the Alquist–Priolo Act (1972), which defined limited setbacks of roughly 15–50 m from mapped traces. Yet the NEHRP approach implied by SDC E and F and by the geometry illustrated in Commentary C11.4-1 expands these zones dramatically. For shallow reverse faults the projected zero-distance corridor can exceed 10 km, encompassing entire urban basins. While such conservatism might be rational for essential or high-risk facilities, it renders the prohibition unrealistic for ordinary development. The following section 11.8.2 acknowledges this by allowing construction in moderate categories (SDC C–D) subject to geological characterization rather than practical guidance. The disparity between these extreme prohibitions and practical urban reality underscores the need for refined, displacement-compatible design criteria.

4.2.3.4 *Taiwan - Active Fault Regulation and Construction Practice*

Following the 1999 *Chi–Chi* earthquake, which ruptured the surface by several meters at the primary source, and widespread secondary fissuring along the Chelungpu Fault system, Taiwan incorporated explicit active-fault provisions into its seismic regulation framework. The Building Technical Regulations (MOI, 2010) and Article 262 of the *Building Act* require that sites within designated active-fault zones obtain a geological investigation and safety assessment prior to construction. The policy is implemented through the Central Geological Survey (CGS), which maps active faults and delineates Geologically Sensitive Areas that are legally binding for land-use control (CGS, 2023).

Administrative rules derived from Article 262 define setback distances from the mapped fault trace according to the fault’s potential magnitude, determined by fault size and shaking history:

- Mw ≥ 7.0: 100 m on each side
- Mw 6.0–7.0: 50 m on each side
- Smaller or uncertain faults: 30 m on each side

These distances, introduced after the *Chi–Chi* earthquake and consolidated in the Geological Act, are planning-level restrictions rather than structural design parameters (MOI, 2010; CGS, 2013). These reflect the relatively wide field of deformation observed in Taiwan’s alluvial basins. During 1999, secondary cracking along the Chelungpu Fault extended roughly 200–400 m across the hanging wall alluvium (Chen et al., 2001), validating these broader administrative buffers.

Building restrictions within mapped active-fault zones are graded by structural importance (MOI, 2010):

- Essential facilities (Risk Category IV) such as hospitals, schools, and emergency centers, are prohibited on or within the designated corridor.
- Ordinary buildings (Risk Categories II–III) are discouraged but may be approved if a site-specific geological investigation demonstrates that the planned footprint lies on the footwall or outside subsidiary-fissure zones.
- Light or temporary structures (Risk Category I), including warehouses and agricultural buildings, are permitted in the outer belt, if no foundation elements intersect the mapped fault plane.

A practical question arises: if low-importance or temporary structures are not required to undergo a geological investigation, how can they be built without crossing the fault trace? In practice, compliance relies entirely on the official CGS active-fault maps, which serve as the reference for land-use approval. These maps, produced at scales of 1:5,000 to 1:10,000, indicate a positional uncertainty of the fault trace of around 10 to 25 m in well-constrained areas and 50 to 100 m where geomorphic or trenching evidence is limited. Therefore, the requirement that small buildings not cross the fault can only be satisfied approximately. Enforcement depends on planning maps rather than subsurface verification.

The Seismic Design Specifications also introduces near-fault amplification factors for shaking intensity. These modifiers address shaking only and do not constitute a methodology for PGD design.

Assessment :

Taiwan's system integrates geological mapping, magnitude-based land-use control, and near-fault seismic-load amplification. It recognizes the surface-fault-rupture hazard through mandatory investigation and selective prohibition rather than through displacement-compatible structural design. The absence of a codified engineering procedure for permanent offset leaves this responsibility to professional judgment, posing an institutional gap that continues to motivate research on design methodologies for building over active faults.

4.2.4 Academic and Analytical Approaches

Structural Modelling in Fault-Rupture Analysis

Fault-rupture research mainly concentrates on free-field rupture models and soil-foundation interaction. The structural systems, however, play a critical role in determining the overall performance of a building subjected to PGD. Academic studies typically adopt two complementary approaches to structural modelling: simplified superstructure idealizations to isolate foundation behavior, and full soil-foundation-structure interaction (SFSI) models to capture the transfer of fault-induced deformation into the building frame.

Early centrifuge interpretations and semi-analytical work treated the superstructure as a rigid block, allowing the analysis to focus exclusively on the footing response (Bransby et al., 2008; Anastasopoulos et al., 2009). Although this assumption is appropriate for identifying the foundations' response mechanisms, it does not capture the redistribution of forces within the superstructure. Later numerical studies introduced elastic or elastoplastic frame models, enabling the investigation of column bending, base shear, diaphragm distortion, and residual drift under imposed foundation rotation and differential settlement (Loli et al., 2012; Bouckovalas & Gantes, 2013). These models revealed that even small permanent rotations of the foundation can induce substantial internal forces in the superstructure, often exceeding those generated by inertial shaking.

A refinement appears in 3D finite-element SFSI analyses, which allow simultaneous simulation of the rupture, the nonlinear soil response, the foundation deformation, and the building frame. These models incorporate realistic constitutive laws for soil and structural materials, interface friction, contact loss, and cyclic degradation. Studies using these methods consistently demonstrate three findings:

(1) Rupture deviation is governed by foundation stiffness and vertical load. A heavier structure increases the vertical stress transmitted to the soil, which in turn densifies and stiffens the soil beneath the footing, and encouraging the rupture to divert.

(2) Within the superstructure, the distribution of vertical-load-carrying elements influences how fault-induced differential settlements translate into internal forces. More statically determinate systems tend to admit imposed displacements with smaller induced actions, whereas highly redundant systems develop larger secondary bending and shear under the same foundation distortion.

(3) Fault-induced rotation of the foundation about a horizontal axis tilts the superstructure. Once the building is no longer level, gravity develops a lateral component relatively to the structures' orientation. In a plan-irregular or stiffness-asymmetric building, this lateral component produces additional torsional demands about the vertical axis.

Because fault rupture imposes PGD rather than cyclic loading, performance assessment in academic studies focuse not on force capacity but on strain, curvature, and drift demands. Metrics commonly used include plastic hinge formation at column bases, residual interstorey drift, diaphragm warping, and loss of verticality. Full-height 3D frame models show that once the foundation experiences several degrees of rotation or centimeters of asymmetric settlement, the superstructure may reach serviceability or stability limits even though no element reaches its ultimate strength capacity (Ha et al., 2019).

These structural analyses complement the soil and foundation modelling approaches by showing how ground deformation propagates upward into the building. They also support a shift in design philosophy. Rather than attempting to prevent fault displacement, academic studies increasingly evaluate structures based on their tolerance for imposed deformation. Thus, conceptually leaning towards performance-based design for fault-rupture hazards.

4.2.4.1 *Characteristic Deformation Modes of Rigid Foundations Crossing Faults*

Research by Gazetas, Anastasopoulos, Loli, and Bransby (2007–2013) demonstrated that the complex interaction between fault rupture and a shallow foundation can be represented by three principal deformation mechanisms. Each describes a distinct pattern of stress redistribution at the soil-foundation contact and a characteristic mode of energy transfer as the rupture front approaches. The terminology: bridging, cantilever, and rotation, does not refer to structural geometry but to the dominant stress path that governs the response of the rigid foundation system.

i) Bridging mode:

In this configuration, the fault offset causes a loss of contact beneath the central portion of the foundation, forcing the footing to behave as a high, stiff beam spanning the gap. Bending moments develop across the foundation thickness, with compression at the top and tension at the bottom, consistent with a sagging bend induced by downward gravity loads spanning over a gap. In contrast, rafts are usually designed for the opposite flexure. The load is reintroduced into the soil through two compression zones near the edges of the uplifted region, where bearing pressures and shear transfer reach their peak values. Numerical analyses show that the region experiencing flexure corresponds to roughly one-third of the footing length for typical stiffness ratios (Anastasopoulos et al., 2009). This configuration is often associated with strike-slip or oblique faulting, but could occur at all mechanisms where the foundation crosses the fault from the footwall to the hanging wall. Typical damage to the foundation in this scenario is bending-related in the bridging span that can take up to 7 times more bending moment than the pre-earthquake stage, while these moments are usually in the opposite direction from the ones introduced after the faulting.

ii) Hanging wall cantilever mode:

This configuration occurs mostly for reverse and strike-slip mechanisms, where the foundation of the structures is placed on the hanging wall block. As the hanging wall is thrust upward, contact is lost near the fault trace, and a cantilever-like bending develops in the footing. Loss of support at the interface above the fault causes bearing stresses to concentrate toward the footwall edge above the trace. The effective lever arm of the deformation is about one-sixth to one-quarter of the foundation length (Gazetas & Loli, 2013). This configuration generates the largest local pressures between the foundation and the soil, and the biggest flexure in the foundation as a cantilever high beam, explaining the frequent cracking or uplift of corners observed in centrifuge and field studies.

iii) Rotation mode - compression and shear dominance

When the rupture passes entirely in front of the foundation and the structure rests fully on the hanging wall block, which moves downward in normal faulting and upward in reverse faulting, the foundation experiences primarily rigid-body rotation. This happens due to differential displacement of the soil affected by the faulting interface. Soil contact largely remains, but large shear stresses develop along the trailing edge as the footing tilts. Centrifuge experiments recorded rotation angles of 5–10° for vertical offsets of 0.5–1 m (Bransby et al., 2008; Loli et al., 2011; Bouckovalas & Gantes, 2013). This mode seldom causes structural failure, yet the tilt and redistribution of bearing pressure towards the lower edge of the raft lead to significant serviceability loss. In fact, at times, a gap may open between the toe of the foundation and the soil.

Together these mechanisms form a continuous spectrum of behavior rather than discrete cases. They describe how loads migrate across the soil–foundation interface as the rupture moves relative to the structure. This understanding provided the basis for later performance-based design methods, which aim to control rotation and uplift instead of preventing ground deformation. This response is consistent with the rigid-body tolerance concept (Concept A; Chapter 4.1), in which global stability is maintained through coherent foundation movement.

Strip foundations behave as a one-dimensional counterpart of raft foundations with limited plan width to distribute the load across. In the literature, their long axis is typically aligned parallel to the fault trace. Experimental and numerical studies (e.g., Bouckovalas & Gantes, 2013; Karamitros et al., 2007) show that strip footings tend to develop deeper bending curvatures, larger rotations, and more pronounced gapping along their length compared with wide rafts. The fundamental soil–structure interaction patterns, however, remain unchanged, and strip foundations can therefore be interpreted as a narrower variant of the mechanisms described above.

4.2.4.2 *Pile Foundations Under Surface-Fault Rupture*

Pile foundations respond to fault rupture in a fundamentally different manner from shallow foundations. Their behavior is governed not by uplift or rotation of the bearing layer, but by the soil displacement field generated along the fault-rupture path. As the rupture propagates upward, the soil does not deform along a sharp plane but forms a shear band. This is a narrow zone of intense shear strain within which most of the relative movement between the two fault blocks is accommodated. Soil stiffness inside this band drops significantly, and large vertical and horizontal displacement gradients develop within its volume. Any pile intersecting it is forced to deform according to the imposed ground displacement, largely independent of the faulting regime or inclination (Anastasopoulos & Gazetas, 2010).

When a pile intersects the shear band, the sharp change in soil displacement across the band forces the pile to adopt a double-curvature bending shape, with curvature concentrations above and below the shear zone. This mechanism has been consistently observed in analytical studies (Karamitros et al., 2007), numerical simulations (Loli et al., 2012), and large-scale experiments (Ha et al., 2019). The bending moments generated by this kinematic deformation can exceed those from inertial loading by an order of magnitude, even for lightly loaded piles. Because the demand arises from imposed soil movements rather than superstructure support, pile failure may occur regardless of building weight or stiffness. Shear cracking, rebar yielding, local buckling, and, in severe cases, fracture of the pile cross-section have been documented near the intersection depth (Bouckovalas & Gantes, 2013).

Pile groups amplify these effects. Within a group, piles do not deform uniformly: edge piles closest to the rupture zone attract the largest curvature, while interior piles may remain partly shielded (Loli et al., 2012). If the pile cap is rigidly connected, this non-uniform deformation generates significant load redistribution, causing some piles to unload, others to attract additional axial demand, and the cap to rotate or settle unevenly. Uplift and gapping beneath one side of the pile cap can further increase axial demands on the opposite side. These interactions mean that even a small number of damaged piles would change the global stiffness of the foundation system and impose unintended demands on the superstructure.

The consequences for the superstructure are substantial. Once a pile hinges or loses stiffness at the shear-band depth, the pile cap experiences differential settlement and rotation, which is transmitted directly into the building columns or walls. Centrifuge and numerical studies consistently show that even modest vertical offsets between piles can induce column bending, distort floor diaphragms, and generate permanent drifts in the superstructure (Loli et al., 2012; Ha et al., 2019). In this sense, the primary structural impact of pile damage constitutes serviceability and stability failure, usually not immediate collapse.

Because of the brittleness of these mechanisms and the limited ability of piles to dissipate large PGD, most academic studies conclude that piles are unsuitable for foundations in active fault-rupture corridors (Anastasopoulos & Gazetas, 2010; Bouckovalas & Gantes, 2013). Where deep support is unavoidable for soil improvement, recommended practice includes avoiding placing piles where they may intersect the shear band .

4.2.4.3 *Caissons and Large-Diameter Shafts*

Deep foundations such as caissons and large-diameter shafts share with piles the objective of transferring loads to deeper, stiffer soil layers and achieving base resistance at depth. They also share the same vulnerability: when a surface-rupturing fault propagates through the soil, any deep element that intersects the shear band is forced to accommodate the imposed deformation. However, the way caissons respond differs markedly from piles because of their low slenderness and very high flexural stiffness. While slender piles bend sharply and form localized plastic hinges above and below the shear-band depth, caissons behave as rigid deep bodies that cannot curve sufficiently to follow the differential soil movement (Anastasopoulos & Gazetas, 2010). As a result, the rupture induces concentrated shaft bending at the shear-band intersection and promotes toe rotation or sliding of the entire element rather than distributed curvature along its length.

This stiffness mismatch has direct implications for the superstructure. Because caissons cannot deform compatibly with the soil, the imposed displacement is transmitted upward as horizontal shift or rigid-body tilt of the foundation block. The superstructure then absorbs this movement as column bending, diaphragm distortion, and differential settlement at the base. Unlike piles, which may fail locally while the cap redistributes loads, caissons typically maintain their axial capacity; instead, they compromise the serviceability of the structure by imposing large, permanent rotations that are difficult to correct. The combination of brittle bending at the shear-band depth and limited deformation capacity makes caissons and deep shafts, like piles, poorly suited to locations where the rupture may intersect the foundation. Most academic studies therefore advise avoiding these elements within active-fault corridors unless they can be placed entirely outside the shear-band influence zone.

4.2.4.4 *Special Foundation Concepts in Fault-Rupture Environments*

A limited number of unconventional foundation concepts have been explored in the academic literature as potential means of accommodating fault-induced PGD. These include deliberately rocking shallow foundations, energy-dissipating interfaces, elevated systems supported on jacked or isolated frames, and hybrid mat–pile arrangements. Although these systems operate through different mechanisms, they all aim to modify the transfer of displacement between the ground and the superstructure. Their effectiveness, however, remains highly contingent on configuration and on the compatibility of soil and structural deformation modes.

Rocking foundations allow controlled uplift and rotation of the footing to limit structural demands. While laboratory studies show that rocking can reduce inelastic demand during seismic shaking, its applicability to fault rupture is limited. The PGD imposed by the shear band tend to accumulate rotation rather than dissipate it, and the concentrated soil deformation at the point of rocking can still produce significant differential settlement. Similarly, energy-dissipating or sliding interfaces can protect the superstructure from horizontal displacement but do not eliminate the vertical or rotational components associated with near-surface faulting. Their performance remains difficult to predict where rupture intersects the footprint.

Hybrid mat–pile systems have received more focused attention, largely because they arise in practice when deep support is needed but designers attempt to retain the flexibility of a shallow foundation. Experimental and numerical studies (Loli et al., 2012; Ha et al., 2019) consistently show that this combination is mechanically incompatible with fault rupture. The raft tends to deform according to the shallow-foundation mechanisms described earlier, while the connected piles attract intense kinematic bending at the shear-band depth. As a result, piles may crack or hinge even when the raft remains largely intact, creating a brittle load path that undermines both stability and serviceability. For this reason, academic research and several engineering guidelines caution against the use of mat-pile systems within fault-rupture corridors unless the piles are structurally isolated from the raft.

Overall, these special systems highlight the difficulty of reconciling PGD with deep structural elements. While they offer conceptual alternatives to conventional design, none of them provide a reliably ductile mechanism for accommodating the severe, localized deformation imposed by surface-fault rupture. Their use therefore remains limited and requires careful justification on a case-specific basis.

4.2.5 Tolerance-Based Design Strategies for Surface-Fault Rupture

Because surface-fault rupture imposes large, directional ground movements that cannot be resisted by strength alone, design strategies must focus on how the structural systems can tolerate these deformations while preserving overall stability. Academic work converges around three complementary approaches:

- robust continuous foundations capable of rigid-body response to vertical or horizontal offsets
- Controlled deformation transmission and isolation strategies that limit the transfer of incompatible movements into the superstructure.
- Monitoring approaches that manage risk under uncertainty.

The necessity of each strategy depends strongly on the expected displacement magnitude and its uncertainty. Small to moderate offsets are best handled by robust continuous foundations, larger primarily horizontal offsets benefit from controlled sliding, and large uncertainties justify including monitoring. Very large displacements may remain practically non-mitigatable. Deep foundations generally do not contribute meaningfully to fault-rupture tolerance. Slender piles and shafts can experience severe bending if they intersect the shear band and are therefore typically unsuitable within fault-rupture zones.

A. Robust Raft or Box Foundations as a Practical Basis for Fault-Rupture Tolerance

Experimental and numerical studies are consistent in showing that a continuous raft or box foundation can survive the principal deformation mechanisms induced by fault rupture by stiff load redistribution rather than ductile force resistance (Bransby et al., 2008; Anastasopoulos et al., 2009; Loli et al., 2011; Bouckovalas & Gantes, 2013). The foundation behaves as a unified rigid body. This is the clearest building-scale expression of the rigid-body tolerance response concept introduced in Chapter 4.1. The rigid basis loses support locally, redistributes contact pressures toward the zones where bearing remains, and maintains the relative alignment of the superstructure's vertical elements. Local cracking may occur, but the superstructure remains stable because the raft limits relative displacement between vertical elements.

The raft withstands the imposed ground deformation by stiffly rerouting loads toward where soil contact persists, thereby preserving a single, coherent load path. Box foundations operate on the same principle as rafts do.

An important insight from academic studies concerns foundation plan geometry. Centrifuge and finite-element work (Loli et al., 2011; Bransby et al., 2018) shows that rectangular rafts with their long axis parallel to the fault trace can promote rupture diversion by creating an extended compression zone that the shear band circumvents. Aspect ratios on the order of 3–4:1 produce a noticeably stronger diversion effect than square foundations, although diversion cannot be guaranteed.

Drawing from the combined experimental and modelling evidence, several practical design implications emerge:

Key design considerations for continuous foundations:

- Bridging capacity: The raft should be proportioned and reinforced to span approximately one-third of its length when uplift occurs beneath its center.

- Cantilever capacity: For uplift near the edge (hanging-wall case), the raft should be able to cantilever over one-sixth to one-quarter of its length, consistent with centrifuge observations.

- Rotation tolerance: The superstructure should remain stable under 5–10° of rigid-body rotation about a horizontal axis, representing the typical tilt induced by footwall or hanging-wall displacement. High or slender structures would be more sensitive to this tilt.

- Horizontal PGD accommodation: For strike-slip deformation, rectangular foundations with long axes parallel to the fault trace can help attenuate rupture propagation and reduce the likelihood of direct intersection.

These principles constitute the most practical and broadly applicable approach for ordinary structures built near faults with moderate offset potential and long return periods. They require familiar technologies and align naturally with conventional engineering practice.

B. Controlled-Deformation and Isolation Strategies

More specialized academic strategies attempt to shape the deformation pattern transmitted to the superstructure. These do not prevent displacement. Instead, they seek to modify the distribution of internal forces or isolate portions of the structure from incompatible movements.

Sliding and interface-based concepts aim to reduce horizontal shear transfer by allowing controlled rigid-body movement or distributed deformation at the foundation–soil interface (Shahraki et. al, 2024) during strike-slip faulting or lateral-spreading events. Similarly, base isolation placed between the raft and the superstructure can limit the internal forces generated by horizontal PGD. Neither approach addresses vertical offset or rotation about a horizontal axis, and therefore both have limited applicability to dip-slip rupture, where bearing and rotation dominate. These strategies become relevant when the expected horizontal displacement is too large for a simple raft-only solution, or when limiting distortion is critical for the intended performance.

Structural segmentation: Dividing the superstructure into independent blocks separated by movement joints reduces torsional demands and prevents distortion from propagating across the entire structure. Field observations from Chi-Chi (1999) and Darfield (2010) earthquakes indicate that segmented buildings often fare better under differential movement, as each block accommodates rotation and settlement independently.

Overall, controlled-deformation and isolation approaches reflect an effort to steer or limit internal force development.

C. Monitoring and the Observational Approach

Because fault location, slip distribution, and deformation patterns involve inherent uncertainty, academic work increasingly emphasizes the importance of monitoring as part of a tolerance-based design strategy. Monitoring tools such as tilt meters, settlement sensors, strain gauges, GNSS stations, and InSAR deformation measurements enable engineers to track rotation, settlement, or gradual fault creep.

The observational method, adapted from geotechnical engineering, links structural performance to measured behavior. Engineers define acceptable deformation ranges in advance, monitor them during operation, and intervene if thresholds are approached. While monitoring does not explicitly reduce safety factors or design criteria, tying action thresholds to real measured behavior helps avoid overly conservative assumptions when displacement magnitude is highly uncertain.

In summary, tolerance-based design is inherently magnitude-dependent. Robust rafts are appropriate for moderate offsets, controlled sliding helps when large horizontal movements are expected, and monitoring is essential wherever rupture location or displacement is uncertain. These approaches are not mutually exclusive and can be combined depending on site conditions.

4.2.6 Major Project Examples

While surveying real-world engineering practice for the design of conventional structures over active faults, only two sectors were found to contain explicit procedural material: the Japanese nuclear industry and Caltrans bridge engineering. Neither, however, provides applicable guidance for ordinary building foundations, and their contrast highlights the regulatory gap that motivates the present work.

Japan - Nuclear Facilities: Japan is the only country that has developed a structured, deformation imposing methodology for stiff foundations subjected to surface-fault rupture. The JANSI-FDE and NILIM/IAEA-aligned procedures require characterizing capable faults beneath or near a site, defining design-basis and beyond-design-basis displacements, checking foundation ground stability, and applying the imposed fault offset directly to a basement-superstructure model. These provisions exist solely because of the extreme consequences of failure at nuclear facilities and the presence of legacy plants in complex tectonic settings. They are not intended for, nor transferrable to, ordinary buildings. Their relevance here lies only in demonstrating that deformation-based assessment of stiff foundations is technically feasible when performance requirements justify the effort. Such examples exist only because avoidance is not feasible in Japan. In most jurisdictions, nuclear facilities located this close to an active fault would not be permitted at all.

California – Transport Agencies (Caltrans): In contrast, agencies with globally advanced seismic practices, such as Caltrans, LA Metro, Caltrain, and the California High-Speed Rail Authority, address fault rupture almost exclusively for bridges and tunnels. Ordinary railway-associated buildings (stations, depots, substations, operations centres) are designed only for seismic shaking in accordance with ASCE 7/CBC. No imposed-displacement checks are required, and no guidance exists for foundation design under fault rupture. The prevailing assumption is that such structures will simply be sited away from active fault traces identified during corridor planning. This approach reflects practical constraints rather than a belief that the buildings could not be engineered, and it underscores the absence of any displacement-compatible framework for conventional foundations within civil building codes.

Together, these two examples illustrate the current boundary of practice: one sector where fault-rupture design is attempted because it must be, and another where it is avoided because no method exists. This contrast reinforces the need for a conceptual foundation-level design philosophy for ordinary structures located near active faults.

4.2.7 Conclusion

Surface-fault rupture imposes PGD that cannot be resisted by structural strength. The governing design principle is therefore tolerance to imposed PGD. Structural systems must tolerate, rather than counteract, the vertical and horizontal offsets imposed by the fault. Across the evidence reviewed, experimental, numerical, and analytical, three practical strategies emerge as the most coherent engineering methods presently available for buildings located near active faults. These methods are Robust shallow continuous foundations, controlled sliding or base isolation for large horizontal offsets, and monitoring-based observational approaches where displacement uncertainty is unavoidably high.

Of these, continuous raft or box foundations provide the most reliable basis for tolerating vertical and oblique fault movements while preserving life safety within it, but usually losing serviceability. Their behavior aligns with the fundamental deformation mechanisms identified earlier in this chapter. Sliding interfaces and base isolation offer complementary value when horizontal PGD dominate, while monitoring provides the only design response to the high uncertainty in rupture location and magnitude. Together, these strategies form an emerging "toolbox" for tolerance-based design, even though none is currently integrated into any building code.

A central finding of this chapter is therefore the near absence of codified design guidance for ordinary buildings under surface-fault rupture. No national or international building standard provides explicit checks, displacement limits, or compatibility criteria for stiff shallow foundations. In most jurisdictions, building close to an active fault trace is simply not permitted. For an instance - in California, fault rupture design is addressed for bridges and tunnels but not for building foundations. Because building codes evolve slowly, often across few decades cycles, the absence of building-level rupture provisions in the forthcoming code generation implies that this regulatory gap may persist for many years. Without explicit guidance, displacement-compatible design for ordinary structures will continue to rely on judgement rather than codified practice.

At the same time, the mechanisms governing building response are understood. Centrifuge and numerical studies consistently show that soil, foundation, and superstructure act as a single coupled system, and that vertical and horizontal PGD induce distinct but predictable patterns of uplift, rotation, shearing, and bearing loss. Both displacement components can be structurally damaging. Vertical offsets often dominate due to rotation-induced serviceability loss, while large horizontal offsets drive shear incompatibility and torsional demands. Yet the greatest barrier to design remains not the mechanics themselves but the uncertainty of rupture geometry. This is why, as discussed in Chapter 3, investigation quality governs which responses are even rational to consider: uncertainty can often be reduced, but rarely eliminated. Fault location, shear-band width, slip distribution, and recurrence cannot be determined with the precision required for deterministic checks.

In summary, this chapter shows that although the behavior of shallow foundations under fault rupture is now conceptually conceived, no codified engineering pathway exists for translating this knowledge into routine building design. Robust rafts, controlled sliding, and monitoring therefore represent the current limit of practical tolerant design strategies for conventional structures near active faults. The need to articulate a coherent design philosophy under uncertainty motivates the broader objective of this thesis: establishing rational principles for tolerance-based structural design near active faults.

4.3 BURIED PIPELINES

4.3.1 Background

Buried pipelines in seismic environments may be both indispensable and vulnerable. Many of these lines are required for use right after a large seismic event for energy and resources. Unlike discrete structures or bridges and roads that can be discretized, pipelines form continuous systems that extend for tens to hundreds of kilometers and can't be segmented. This continuity creates both strength and vulnerability. On one hand, a pipeline can redistribute strains over long distances, allowing ductile materials to deform plastically rather than fracture immediately. On the other, continuity makes it almost impossible to design away a shear zone crossing. When an infrastructure intersects an active fault trace, the line itself cannot avoid the relative displacement of the shear zone unless its alignment is completely diverted.

Pipelines are not only critical in ordinary times but they become even more essential after seismic disasters, when demand for water and energy typically increases. Hospitals, emergency shelters, and rescue operations require uninterrupted energy supply, while firefighting needs surge in earthquake-stricken cities. Post-disaster surveys in Japan have shown lifeline consumption rising to as much as twice normal levels in the immediate aftermath, precisely when supply is most fragile (Shoji & Tatano, 2013). This paradox like behavior underscores the necessity of performance-based design, in which pipelines are engineered for displacement compatibility when they unavoidably cross active faults. Rather than assuming such crossings can be avoided, design practice can explicitly accommodate PGD through strain-based criteria and fault-tolerant detailing. In many seismically active regions, including southern Europe, Japan, north America and Chile, domestic gas is piped to households where housing stock such as timber is common (O'Rourke & Jeon, 1999; Pitilakis & Tsinidis, 2014). The combination of seismic rupture, damaged gas lines, and flammable dwellings has historically led to devastating urban fires, as in San Francisco in 1906 and Kobe in 1995 (Lawson, 1908; Scawthorn, 1986; Scawthorn & Gupta, 1997). This vulnerability represents a broader challenge across earthquake-prone societies that rely on piped natural gas for domestic energy.

The main types of buried lifelines that may intersect active fault traces include:

- Water pipelines, wastewater and sewer pipelines.
- Fuel and natural gas transmission pipelines.
- Crude oil and petroleum product pipelines.

For buried pipelines, the governing demand is PGD rather than transient shaking. Whereas seismic waves typically induce relatively small, distributed soil-pipe strains, PGD imposes large displacement gradients over short lengths. At fault crossings, imposed offsets can exceed pipeline strain capacity by orders of magnitude, far beyond the few-percent tensile ductility and the slenderness-controlled compressive limits of steel pipes (ALA, 2005). In such cases, performance cannot rely on resisting the displacement. It must be achieved through displacement compatibility, by accommodating and/or redistributing deformation along the pipe–soil system.

The typical failure modes due to PGD are well-documented across historical earthquakes (O'Rourke & Wang, 1977; Uckan et al., 2024):

- Tensile rupture – when axial elongation exceeds the tensile strain capacity of the pipe wall or the pull-out resistance of joints. This often produces full circumferential cracks, as seen in San Fernando (1971) and Niigata (1964).
- Compressive buckling and wrinkling – when compressive strains surpass the critical buckling threshold, leading to wall wrinkles, and sometimes tearing, as observed in the 1999 Izmit water main and in the 2023 Sogutlu crossing (Uckan et al., 2024).
- Ovalization – deformation of the circular cross-section into an ellipse, reducing hydraulic capacity and predisposing the pipe to collapse.
- Joint pull-out or shearing – common in cast iron and asbestos–cement pipes with rigid joints; the 1971 San Fernando earthquake produced thousands of such failures (O'Rourke & Wang, 1977).
- Weld tearing – concentrated bending can initiate tearing at welds in welded steel lines, documented in natural gas pipelines during the 2023 Kahramanmaraş earthquake (Uckan et al., 2024).
- Connection failure at structures – valve chambers, pumping stations, and culverts are stiffer than the pipe; relative movement during PGD causes leaks or pull-outs, as observed in Taiwan (MOI, 2010) and Türkiye (Uckan et al., 2024).

These failure mechanisms illustrate that pipelines are not simply another structure type subject to seismic design. Their continuous nature, dependence on soil support, and role as lifelines amplify both their vulnerability and their criticality. Unlike bridges or buildings, where damage is mostly localized, the failure of a single buried pipe segment can propagate consequences through entire network. The following sections summarize the main codified design approaches for pipeline fault crossings as well as the ways academic research extends these approaches through performance-based and probabilistic treatments of fault displacement and soil–pipe interaction.

4.3.2 Codes and Guidelines

This section summarizes the principal codified guidance used in practice for buried pipelines crossing active faulting zones. The focus is on how design fault displacement is defined including the recommended acceptqnce criteria, and how soil–pipe interaction is represented for analysis.

American Lifelines Alliance (ALA) – Guidelines for the Design of Buried Steel Pipe (2005)

The American Lifelines Alliance (ALA) guidelines were commissioned by the Federal Emergency Management Agency (FEMA) and prepared under the American Society of Civil Engineers (ASCE) to consolidate U.S. practice for lifeline design under seismic and geotechnical hazards for lifeline infrastructure. Published in 2005 as FEMA Report 508, the document synthesised decades of research, testing, and post-earthquake observations of buried steel pipelines. Field evidence from the 1971 San Fernando and 1994 Northridge earthquakes revealed that most buried pipeline damage resulted from PGD rather than transient shaking, demonstrating the need for strain-based, deformation-controlled design methods (O'Rourke and Liu, 1999; ASCE TCLEE, 1999; ALA, 2005). Field data and internal guidelines from PG&E (2002), SoCalGas (1998), and LADWP (2000) were synthesized by the ASCE Technical Council on Lifeline Earthquake Engineering and formalized through the ALA program. The resulting document is not a legally binding code but a national standard of practice, widely adopted by utilities and infrastructure agencies.

While the guideline includes general chapters on material properties and load combinations, only Chapters 7 and 8, together with Appendices A and B, explicitly address PGD, the governing damage mechanism at fault crossings:

- Chapter 7 presents the design models for pipeline response to PGD, distinguishing between transmission and distribution systems and defining four Function Classes that rank pipelines by their importance to public safety and service continuity.
- Chapter 8 elaborates on Chapter 7 focusing on large-diameter welded steel transmission lines, providing additional hazard definition, return-period guidance, and recommendations for the use of advanced numerical analysis.
- Appendix A contains the simplified analytical methods for fault-crossing analysis.
- Appendix B provides the nonlinear soil–spring parameters required for those methods. Together, these four sections form the analytical core of the ALA's fault-crossing methodology.

Pipeline classification: Chapter 7 distinguishes between transmission pipelines (large-diameter, high-pressure, welded steel lines essential to regional supply) and distribution pipelines (smaller, lower-pressure, often flexible or jointed systems). Analytical verification is required for transmission lines, whereas distribution systems are evaluated qualitatively for flexibility and repairability.

Function Classes: Four Function Classes (I–IV) define the importance of a pipeline and control the level of analysis required:

i) Class I – minor or local distribution lines.
ii) Class II – standard transmission pipelines
iii) Class III – major transmission or inter-regional pipelines
iv) Class IV – essential lifelines serving critical facilities.

Each class corresponds to different reliability targets, analysis complexity, and return periods for design fault displacement.

Design fault displacement: derived from geotechnical characterization of the active fault. It is applied as a prescribed boundary condition in the analysis. The magnitude of displacement depends on pipeline importance: service-level (≈10% in 50 years), design-level (≈2% in 50 years), and maximum credible displacement (deterministic upper bound). Chapter 8 associates these levels with Function Classes to define return period for the transmission lines.

Design models: Chapter 7 presents three distinct analytical models for PGD design each suited to different levels of hazard certainty, importance, and geometric complexity:

- Chart Method: A prescriptive, table-based procedure used to select design categories and construction styles according to Function Class and PGV or PGD level.

It is suitable only where the seismic hazard is well characterized and of high certainty, such as sites with mapped faults and defined displacement magnitudes.

The method provides guidance for distribution and less critical transmission pipelines but does not compute stress or strain explicitly.

- Equivalent Static Method: A simplified analytical approach that employs closed-form mechanics to estimate pipeline forces, displacements, and strains. It assumes uniform soil restraint, regular geometry, and known fault offset, and is primarily used for preliminary or routine design of standard transmission lines.
- Finite Element Method: A nonlinear numerical simulation of the pipe-soil system that resolves strain, curvature, and local buckling effects. It may be applied to any pipeline but is generally required for Function Class III–IV transmission pipelines.

Advanced nonlinear analysis (Chapter 8): Chapter 8 elaborates the three design models for transmission pipelines, giving detailed nonlinear analysis guidance for fault-crossing conditions. It specifies how to apply fault displacement within a numerical model, limiting element length to one pipe diameter within the fault-influenced zone, and extending the model 10–15 diameters beyond the deformation zone on each side to ensure realistic soil–pipe anchorage. The chapter refers to the nonlinear soil–spring curves of Appendix B and requires verification of local strain peaks against the acceptance limits.

Simplified analytical methods (Appendix A): Appendix A provides closed-form and semi-empirical equations for axial and bending strain distribution along pipelines crossing active faults. Boundary conditions are given for strike-slip, normal, and reverse faults, with non-dimensional strain–displacement charts and correction factors for crossing angle and burial depth. The method integrates soil stiffness values from Appendix B and yields conservative strain estimates compared to full numerical analysis.

Soil–pipe interaction (Appendix B): Appendix B defines nonlinear spring relationships for three directions of interaction—axial (t–z), lateral (p–y), and vertical (q–z). Ultimate resistances depend on soil type and density, and parameters are tabulated for sands and clays of varying compaction. Adjustment factors for engineered backfill are also provided to control restraint near faults.

Material properties: Pipe steel is modeled as elastic–plastic with strain hardening, and the D/t ratio governs the limits for local buckling and wrinkling.

Acceptance criteria: Tensile strain: 3% for standard design; up to 5% for high-ductility steel. Compressive strain: 1% or 20·t/D (%), whichever is smaller. Bending strain: corresponding to local wrinkling onset based on D/t relations (§7.3.4).

Mitigation and reporting: When calculated strains exceed allowable values, mitigation may include rerouting, wall-thickness increase, improved backfill, or flexible couplings. Reports must document displacement assumptions, soil data, model parameters, and verification of strain limits.

Assessment

The ALA guidelines introduced a consistent analytical structure that remains the foundation of modern pipeline design for fault crossing. The document unifies geotechnical input, structural modeling, and material performance into a single, reproducible process. Although it predates widespread use of the term, the formal adoption of 'performance-based design' terminology, it embodies the same philosophy: demand definition (ground displacement), system modeling (pipeline deformation), and capacity verification (strain capacity). This displacement-controlled, strain-verified procedure defines pipeline performance in terms of serviceability, repairability, and containment, shifting verification from force-based checks to strain-based limits. The clear distinction between pipeline function classes and analysis methods ensures that design effort scales with societal importance and risk. The ALA thus transformed empirical Californian practice into a fully articulated analytical and performance-based framework that continues to inform both U.S. and international standards.

Japan – Seismic Design for Buried Pipelines

Japan's lifeline design practice is not codified in a single national law but is governed by industry standards widely adopted by utilities. The Japan Gas Association (JGA) issues guidelines for gas transmission and distribution pipelines, while the Japan Water Works Association (JWWA) and municipal utilities publish guidance for water supply systems. These documents, though voluntary, are treated as de facto national standards for seismic design and are used across Japan by utilities and contractors (Kiyomiya, 2010; O'Rourke et al., 2008). Their development was driven by repeated earthquake damage to lifelines and the recognition that essential networks must remain operational after major seismic events. The guidelines adopt a two-level seismic performance framework: under Level 1 (moderate, frequent shaking), pipelines must remain fully functional; under Level 2 (rare, extreme shaking or fault rupture), limited and repairable damage is acceptable provided that it does not cause catastrophic failure or prolonged loss of service. Although prepared by different organizations, the gas and water guidelines share a common engineering philosophy-strain-based, performance-oriented, and displacement-compatible design-supported by extensive full-scale testing and post-earthquake observations. Treating them together is appropriate because both derive from the same national research base and employ comparable analytical and detailing principles for ductile, fault-tolerant behavior.

Guidance for buried pipes design at fault crossings:

Common principles for both gas and water systems:

Hazard characterization: identify active faults, liquefaction, and lateral-spreading zones; determine PGD from geological investigation and past fault movement records.

Analysis methodology- Two complementary approaches are used for evaluating pipeline deformation under fault displacement or other PGD:

Simplified analytical methods:

Assumptions: The pipe is modeled as a continuous buried beam following Euler–Bernoulli flexure relationships, assuming uniform soil conditions and idealized nonlinear soil-spring resistance. Soil behavior is treated as bilinear, with mobilized resistance capped at an ultimate limit.

Method: Closed-form or semi-empirical solutions are used to estimate axial and bending strains generated by imposed fault displacement. Fault movement is represented as a prescribed ground offset, and the pipeline response is obtained by integrating strain and curvature along the deformed shape.

Criteria: Calculated maximum strains are compared with material acceptance limits. The method is primarily used for preliminary or routine design, where expected offsets are moderate and geometry is regular. Simplified methods have been shown to yield conservative strain estimates relative to full numerical models (ALA, 2005; O'Rourke & Liu, 1999; Suzuki et al., 2004).

Nonlinear numerical analyses:

Assumptions: Soil–pipe interaction is represented by nonlinear springs (axial, lateral, and vertical) or continuum soil models capturing plastic deformation. The pipe may be modeled using beam, shell, or solid elements, depending on detail required.

Method: Incremental ground displacement is applied to simulate fault movement until strain and curvature demands converge. The approach allows direct simulation of local buckling, joint behavior, and soil yielding.

Criteria: Results are checked against acceptance limits—tensile strains typically within 2–5%, compressive strains limited by local buckling to approximately 1% or 20·t/D (%), whichever is smaller. This method is used for complex geometries, major fault offsets, and qualification of special components.

Positioning and restraint control: orient the line to promote tensile deformation at crossings, minimize burial depth locally, and use controlled granular backfill and smooth coatings to reduce soil restraint and avoid localized contact pressures.

Operations and resilience: provide sectional isolation, redundancy, and practical access for inspection and repair.

Distinct features:

- Gas pipelines (JGA 2004): applicable to welded steel lines for high-pressure transmission and distribution. Two seismic motion levels are defined for verification. Strain limits depend on D/t ratio and steel grade, and verification is performed through nonlinear analysis or simplified strain evaluation. Flexible joints are generally limited to interfaces, with continuous welded sections relying on steel ductility.

- Water pipelines (JWWA, ERDIP, SPF): applicable to ductile-iron and steel water mains. Emphasis is on fault-tolerant components—flexible or expansion joints with defined axial and rotational capacity, and proprietary systems such as ERDIP and SPF, which accommodate several meters of offset through localized deformation. Controlled backfill and coatings are required to reduce applied loads and prevent point pressures. Full-scale testing qualifies system performance and verifies fault-crossing capacity.

Assessment

Japan's seismic design for buried pipelines forms a mature, empirically validated framework grounded in clear performance objectives. It integrates analytical verification with tested components, ensuring that deformation is concentrated in predetermined, ductile regions while maintaining overall integrity. The combination of strain-based design, advanced analytical tools, and proven construction technologies provides a coherent national methodology for achieving displacement-compatible lifelines. Within the response concepts defined in Section 4.1, Japanese pipeline guidance aligns most closely with Concept C (displacement-compatible detailing), verified through strain-based acceptance criteria under imposed ground displacement.

Eurocode 8 – Part 4 (EN 1998-4: Silos, tanks, pipelines, 2006)

Eurocode 8 is the harmonized European seismic design code, mandatory in EU member states since 2010. Part 4 addresses silos, tanks, and pipelines. Although Eurocode as a whole is framed within a limit-state philosophy with partial factors, the provisions for pipeline fault crossings (clause 6.6) are not formulated in performance-based or capacity-design terms. Instead, the code prescribes measures that can best be described as positioning: orientation of the line relative to the fault, burial depth, wall thickness near the trace, quality of backfill, and avoidance of bends or anchoring details. These measures concern how the pipeline is laid out in relation to the fault, but the code provides no methodology for analysis or criteria to verify whether such positioning achieves an target performance.

Guidance for buried pipes design at fault crossings: Eurocode 8 sets quantitative strain acceptance limits for pipelines under PGD: 3% in tension, and in compression the smaller of 1% or $20 \cdot t/D$ (%), where t is wall thickness and D is pipe diameter. Section 6.6 then prescribes detailing measures to improve survivability at fault crossings:

Orientation:

- across strike-slip faults place the pipeline at an angle that applies tension on the pipe under PGD.
- For reverse faults, minimize the intersection angle to reduce compression.
- Where mixed strike-slip and reverse motion is possible, choose an angle that promotes tensile elongation.

Burial depth: minimize depth at the faulting zone to reduce soil restraint.

Wall thickness: increase wall thickness within 50 m of the fault trace to increase displacement capacity. (100 m over all)

Interface friction: reduce soil–pipe friction (e.g., by smooth coatings) to reduce applied loads on the pipe.

Backfill: control backfill over 50 m each side of the fault, using loose to medium granular soils without cobbles or boulders to reduce localized stresses. If natural soils are unsuitable, oversize trenches (~15 m each side) should be excavated and replaced.

Welded steel pipelines: These may deform well into the inelastic range in tension; layouts should avoid compression and favor tension plus moderate bending. Compressive strains must be limited to wrinkling or local buckling thresholds.

Alignment: keep crossings straight; avoid bends, elbows, or flanges that would anchor the pipe.

Assessment

The fault-crossing guidance in Eurocode 8 is limited to positioning decisions. It provides a checklist of measures to orient, bury, and detail the pipe in ways that allow tensile ductility, but it does not include analytical tools, demands quantification, or quantitative performance objectives. The crossing criteria address only PGD in its static form. No consideration is given to the dynamic component of the phenomenon. EC8 functions as a prescriptive reference for pipeline placement, but cannot be regarded as a performance-based design framework.

New Zealand – Seismic Design for Buried Pipelines

In New Zealand, seismic design practice for buried lifelines is shaped by frequent exposure to major earthquakes and a strong national emphasis on resilience and recovery. There is no dedicated prescriptive code for buried pipelines. Instead, practice is guided by the New Zealand Society for Earthquake Engineering (NZSEE) Guidelines for Lifeline Utility Earthquake Engineering (1999, updated 2017), together with the continuing work of the New Zealand Lifelines Council and the Ministry of Civil Defence and Emergency Management (MCDEM). While the national loading standard NZS 1170.5 defines earthquake actions for structural design in general, it does not provide specific provisions for buried pipelines. As a result, buried-lifeline design relies primarily on qualitative principles established in NZSEE and Lifelines guidance. These frameworks evolved following repeated lifeline damage in the 1987 Edgecumbe, 2010–2011 Canterbury, and 2016 Kaikōura earthquakes, and they emphasize network resilience, rapid repair, and coordination among engineers, asset owners, and emergency planners. The NZSEE guidelines therefore function as a de facto national reference for buried lifelines, stating performance expectations for service continuity rather than prescribing detailed design criteria (NZSEE, 2017; New Zealand Lifelines Council, 2018).

Guidance for buried pipelines at fault crossings:

New Zealand guidance does not prescribe fault-crossing design measures or analytical methods. Neither NZS 1170.5 nor the NZSEE Lifeline Utility Earthquake Engineering Guidelines specify strain limits, geometry rules, or soil–pipe interaction models for fault displacement. Instead, they outline broad performance principles—flexibility, ductility, repairability, and continuity of essential services after earthquakes. In practice, these principles are complemented by international methodologies, particularly American Lifelines Alliance (ALA) guidance and Japanese practice, which New Zealand engineers commonly reference when quantitative verification or detailing is required. Consequently, national practice typically adapts established external methods within a resilience-based planning culture that prioritizes rapid restoration and institutional coordination over codified pipeline fault-crossing rules (NZSEE, 2017; MCDEM, 2018).

Assessment

The New Zealand framework represents a mature resilience philosophy rather than a prescriptive pipeline design standard. It sets clear performance expectations—buried lifelines should remain functional or repairable after major earthquakes—but leaves analytical procedures and design details to professional judgment. The absence of explicit numerical criteria or standardized modeling requirements reflects a national emphasis on collaboration and preparedness rather than regulatory enforcement. In practice, this leads to a system in which international analytical methods (e.g., ALA or Japanese guidance) are adapted to local conditions to support service continuity and rapid recovery. New Zealand's contribution therefore lies primarily in institutional coordination and integration of engineering judgment with civil-defence planning rather than in developing new prescriptive fault-crossing methodologies (NZSEE, 2017; New Zealand Lifelines Council, 2018).

4.3.3 Academic and Analytical Approaches

Academic research treats fault-crossing design of buried pipelines as a performance-driven problem under uncertainty, rather than as a deterministic verification against a single prescribed displacement. In most design standards (e.g., Eurocode 8-4 and ALA guidance), the engineer selects a design fault offset (Δ_{design}) and verifies that the resulting pipe strain remains below a prescribed allowable limit. By contrast, contemporary studies more often adopt performance-based or risk-oriented frameworks, in which fault displacement demand and system response are evaluated across multiple hazard levels and performance states.

Performance-based design (PBD)

In a PBD framework, a pipeline crossing an active faulting zone is treated explicitly as a displacement-compatibility problem. The system is required to satisfy distinct performance objectives - typically operability, containment, and life-safety - under specified levels of fault-displacement hazard. Fault displacement demand is quantified probabilistically using Probabilistic Fault-Displacement Hazard Analysis (PFDHA), which provides distributions of expected surface slip for a given return periods (Youngs et al., 2003).

For selected displacement percentiles (or hazard levels), nonlinear soil-pipe interaction (SPI) analysis is used to compute strain demand along the pipe. These demands are then compared against strain capacities associated with the corresponding performance states (O’Rourke & Jeon, 2015; Ni et al., 2020). This multi-state demand–capacity verification replaces a single deterministic displacement check with explicit reliability and post-event serviceability targets.

Risk-oriented design

Risk-oriented frameworks extend performance-based verification by explicitly incorporating consequences. By combining hazard, fragility, and consequence models, researchers estimate annualized failure probability and/or expected annual loss (EAL), enabling cost–benefit comparison of mitigation options (Ni et al., 2020). In water and gas transmission systems, this allows a decision maker to weigh, for example, the cost of a low-restraint trench or specialized joints against the reduction in expected annual loss. Although risk-based design is not yet codified, it represents a prevailing academic direction, complementing strain-based performance checks with explicit economic and reliability metrics.

purely deterministic verification is used in research mainly for benchmarking and model validation. The academic consensus treats fault-crossing design as a probabilistic, performance-based problem in which demand, capacity, and consequence are evaluated jointly, rather than as a single prescribed-displacement check.

Loading

Design standards typically represent fault rupture as a single static loading event, applying a prescribed PGD profile to the pipe–soil system. Academic work instead treats loading as a sequence with distinct stages:

i) Transient shaking that may induce curvature or ovalization.
ii) Co-seismic rupture (PGD) that imposes the primary offset.
iii) Post-seismic after-slip or creep that can continue for hours to years.

Quantitative comparisons indicate that the third stage can be non-negligible: along the Hayward Fault, USGS modeling suggests median co-seismic slip < 0.2 m but after-slip up to ~1.0 m in the days following rupture (Graymer et al., 2019). For creeping segments, post-seismic deformation may therefore exceed the co-seismic offset, while current design standards do not explicitly account for it.

Modeling

Both design standards and academic research commonly represent soil–pipe interaction using a Winkler beam-on-springs formulation. Laboratory and centrifuge studies indicate that this simplified framework reproduces overall force–displacement response with sufficient accuracy for design applications (Ha et al., 2019). As a result, research has largely reinforced the codified modeling approach.

Where research extends practice is in quantifying the parameters that govern the nonlinear spring backbones. Experiments show that backfill density, trench width, and interface conditions can change peak soil reaction by factors of roughly 1.5–2 and shift effective anchor length by approximately 30–40%. These sensitivities help explain the scatter in empirical spring representation without undermining the method itself. Instead, they support the recommendation to apply the same nonlinear-spring model with project-specific calibration for critical crossings and standard parameters elsewhere (Melissianos & Gantes, 2019).

Detailed finite-element analysis (FEA) is therefore not a separate design philosophy but a higher-fidelity numerical implementation of the same soil–pipe interaction principles. The ALA guidelines cite FEA as an optional verification tool for complex geometries or Function Class III–IV pipelines, without prescribing specific element formulations or constitutive models. Academic studies similarly use FEA primarily for research and validation, including simulation of local wrinkling, ovalization, and gapping, and for calibration of simplified spring-based models.

Criteria

The fixed strain limits used in design guidance (typically ~2–3% in tension and ~1% in compression) can be interpreted as simplified expressions of three underlying academic limit states:

i) tensile fracture of base metal or welds.
ii) local buckling or wrinkling with ovalization.
iii) Serviceability.

Parametric studies (Vazouras et al., 2012; Melissianos & Gantes, 2019) indicate that these unified limits are generally conservative in tension for high-toughness, pressurized pipes, but they can be nonconservative in compression for thin-walled sections (D/t > 60) or in the presence of ovalization.

Design standards therefore inherit simplified single-number limits that reflect median academic outcomes but do not capture their dependence on D/t, internal pressure, and soil restraint.

Interaction

Studies that examine combined mechanisms indicate that ground strain from shaking rarely exceeds ~10^{-4} for realistic peak ground velocities and Rayleigh-wave speeds ratio (O'Rourke & Liu, 1999).

$$\varepsilon \leq \frac{PGV}{C_R}$$

By contrast, PGD-induced pipe strains at fault crossings are typically on the order of 10^{-3}–10^{-2}. Direct superposition of shaking strain onto PGD strain is therefore generally negligible. Shaking may nonetheless influence fault-crossing response indirectly by introducing small curvature or ovalization that reduces the compressive buckling threshold during subsequent fault displacement (Karamitros et al., 2007; Bouckovalas & Gantes, 2013). In academic treatments, this coupling is represented as reduced imperfection tolerance or reduced buckling capacity, rather than as linear addition of strain demand.

Time influence

Laboratory and modeling studies indicate that both steel and soil exhibit rate sensitivity within strain-rate ranges that may be relevant to near-fault deformation.

Pipeline steel - Dynamic tests show that increasing strain rate from quasi-static ($\sim 10^{-3}\ \mathrm{s}^{-1}$) to dynamic loading ($\sim 10^{-1}\ \mathrm{s}^{-1}$) can increase yield stress by ~10% while reducing uniform elongation capacity by ~5–8%, producing a stiffer and less ductile response (Yoon et al., 2016). Rate-dependent plasticity models incorporate this behavior explicitly (Kyriakides & Corona, 2007).

Soil - In saturated fine backfills, undrained strength increases approximately with the logarithm of shear rate; a tenfold rate increase can raise peak resistance by roughly 20–40%, which can proportionally increase axial strain demand in the pipe-soil system (Ha et al., 2019).

These strain-rate ranges can be grounded in published time-history results. Liu and Jia (2012) derived fault-displacement time histories from near-fault recordings (after baseline correction) and used them as dynamic input to a buried pipeline fault-crossing analysis. Using their reported strain time history from the CHI-CHI earth quake, the maximum axial strain increases from 0.2332% to 0.5625% between $t = 6–7$ s, implying a characteristic strain rate of approximately $3.3\times10^{-3}\ \mathrm{s}^{-1}$ during the rapid deformation phase. By contrast, post-seismic deformation proceeds at quasi-static rates, where time-dependent soil relaxation and long-term accumulation may govern rather than dynamic strengthening. Academic studies therefore consider both rapid loading during fault movement and slower time-dependent accumulation, whereas most design guidance remains effectively rate-independent.

Monitoring and adaptive management

Academic and applied work increasingly treats monitoring as part of the life-cycle management of fault crossings rather than a purely post-construction activity. Distributed fiber-optic sensing (DFOS) and in-line strain instrumentation can provide direct measurement of pipeline response (e.g., distributed strain, temperature, and acoustic signatures) along critical segments. Satellite InSAR can complement these systems by providing corridor-scale measurements of surface deformation, which are useful for screening and prioritizing locations affected by subsidence, landsliding, or creep. Accordingly, monitoring supports an observational approach: key assumptions about ground movement and soil restraint can be checked against measured behavior, and inspection or intervention can be targeted where deformation is detected. While current standards do not permit relaxation of acceptance criteria solely on the basis of monitoring, instrumentation can improve confidence in hazard characterization and support risk management through detection and intervention rather than reliance on conservatism alone.

Conclusion

Academic research frames buried pipeline fault crossings as a displacement-compatibility problem in which performance is evaluated under uncertainty across multiple hazard levels and performance states. Rather than treating faulting as a single static action, the loading history is considered explicitly, distinguishing transient shaking, co-seismic PGD, and the potential for post-seismic deformation to accumulate after the main rupture. Soil-pipe interaction is modeled as a nonlinear, system-dependent process in which effective restraint and demand localization depend on trench geometry, backfill properties, and interface conditions, motivating calibration where consequences are high. Strain-based acceptance is interpreted as an envelope of interacting limit states whose governing parameters depend on pipe geometry, internal pressure, and restraint conditions. Shaking-induced strains are typically small compared with PGD-driven demands at fault crossings, but shaking can still influence subsequent response indirectly by introducing imperfections that reduce compressive buckling tolerance during fault displacement. Rate effects are also recognized: both steel and soil can exhibit loading-rate sensitivity, so deformation capacity and effective soil resistance may differ between rapid co-seismic loading and slower time-dependent deformation. Overall, the literature portrays buried pipelines as coupled, time-dependent soil–structure systems best assessed through multi-state, probabilistic performance verification, with life-cycle risk management informed by observed behavior where monitoring data are available.

4.3.4 Conclusion

Buried pipelines exemplify Concept C in the response framework of Section 4.1: performance at fault crossings is governed primarily by displacement compatibility under PGD, expressed through strain and buckling acceptance criteria rather than force-based resistance. This underlying logic is shared across both practice guidance and the academic literature, although the degree of codification and treatment of uncertainty differ.

In practice, the global regulatory landscape remains uneven. Eurocode 8-4 is the only document in this review that functions as a binding code framework, yet its fault-crossing provisions are primarily prescriptive and provide limited analytical structure for displacement definition and verification. By contrast, the ALA guidelines are not a legally binding code, but they represent the most comprehensive and widely used analytical framework in practice. The ALA formalize classification, define fault-displacement levels, and provide analysis procedures and soil–spring parameters for strain-based verification. Japan’s guidance similarly reflects a mature, performance-oriented practice supported by extensive testing, while New Zealand relies mainly on resilience principles and typically references external methodologies when quantitative verification is required.

Although binding code provisions for fault-crossing pipelines remain limited in many jurisdictions, industry practice is not constrained to avoidance alone. The existence of detailed, operational guidance has allowed practitioners to incorporate displacement-compatible solutions where crossings is preferable.

A consistent theme across research is that the dominant uncertainty is not whether PGD governs, but how displacement demand is defined and how effectively it is transmitted into the pipe through soil–pipe interaction. Investigation inputs identified in Chapter 3 such as fault location, displacement components and directionality, deformation-zone width, and backfill conditions, control the credibility of any assessment. Within the common modeling framework of nonlinear beam-on-springs, soil restraint and cover conditions strongly influence where strain localizes and whether the governing response is tension-dominated or buckling-dominated.

The literature further clarifies that the single-number strain limits commonly reported in guidance should be interpreted as simplified envelopes of multiple interacting limit states, whose controlling parameters depend on geometry, internal pressure, and restraint conditions. Transient shaking typically contributes little to total fault-crossing strain demand compared with PGD, but it can influence response indirectly by introducing curvature or ovalization that reduces compressive buckling tolerance during subsequent fault displacement. Rate sensitivity of both steel and soil is also relevant: deformation capacity and effective soil resistance may differ between rapid co-seismic loading and slower time-dependent deformation, supporting explicit consideration of loading history where it is relevant to the hazard scenario.

Overall, buried pipeline fault-crossing design is best viewed as a coupled, time-dependent soil–structure problem: define the displacement hazard consistently with the performance objective, represent soil–pipe interaction with appropriate calibration at critical crossings, and interpret strain response against the governing limit states for the intended performance level.

4.4 ENGINEERING APPROACH TO ROADS ON ACTIVE FAULTS

In practice, it is often impractical to make a surface roadway fully compatible to large fault displacements. Instead, the prevailing approach emphasizes maintaining corridor-level connectivity even if the pavement and embankment suffer localized damage. This means accepting that a fault rupture may shear and offset the road in a limited zone, while ensuring that no catastrophic collapse occurs and that the route can be restored quickly after an earthquake. Academic and industry literature frames this as a performance-based strategy favoring repairability and quick service restoration over rigidity (Bruneau and Reinhorn, 2007). The road network's function is preserved by planning for quick post-event repairs – an approach fundamentally different from the design of buildings or buried utilities in similar conditions (NZTA, 2018).

This approach corresponds to Concept B (Chapter 4.1): a sacrificial deformation zone is designated where the fault is expected to intersect the road, and this segment is deliberately configured to absorb rupture-induced distortion. Pavement, embankments, and shallow fills within this zone are detailed to fail in a controlled and repairable manner (Bray and Oettle, 2009). More critical segments are isolated or provided with overstrength detailing to reduce their exposure and divert the damage away from them. The result is a discontinuous but recoverable fault-crossing geometry. One that may temporarily lose surface continuity but can be quickly restored to usable condition through grading, fill replacement, or temporary bridging (FHWA, 2006).

Concepts A and C are not generally applicable to roadways. Concept A, which relies on rigid-body coherence through structural stiffness, cannot be applied to extended surface corridors: a road cannot feasibly span an active fault with a monolithic foundation unless it becomes an elevated bridge. Concept C, which requires materials and detailing capable of sustaining large elastic strains, is incompatible with typical road construction. Roads are not made of deformable ductile elements, they consist of layered brittle materials over compacted fill, with no inherent strain capacity. More fundamentally, even if elasticity were achievable, applying concept C-like verification over the full width of a deformation zone would be disproportionate in both engineering complexity and cost.

While seismic shaking can also affect road infrastructure, it is generally a secondary concern in the fault-crossing context. Unlike vertical structures, which are sensitive to inertial amplification, roadways are governed by geometric distortion and residual offset. Their dominant failure mode is misalignment, not collapse.

Finally, economics reinforces the engineering rationale. Sacrificial fault-crossing zones are not just more practical but are also more cost-effective. Designing an elastic or elevated road system to survive rare rupture events would be more expensive than accepting localized damage and planning for repair. This tradeoff of damage acceptance is the essence of the Concept B strategy, and it underpins how fault rupture is managed in road corridor design.

4.4.1 Codes and Guidelines

This section summarises the main agency and standards-based guidance for road corridors crossing active faulting zones, focusing on surface-laid roads, and highlighting the shared emphasis on controlled damage and rapid restoration. Formal technical standards specific to road fault-crossing remain limited. However, several authoritative agencies have developed guidance and procedures that directly influence how surface-laid road segments are planned and designed where they intersect active fault traces. This section focuses on surface-fault rupture and road corridors, not elevated roads on bridges, which are treated separately in most guidelines and are outside the scope of this thesis.

In sum, academic literature reveals a consistent logic: where full resistance is unfeasible, roads should be designed to absorb, isolate, or bypass the effects of fault rupture in ways that prioritize rapid recovery. While individual strategies differ in detail, they converge on the shared objective of minimizing service disruption.

Caltrans Codes and Manuals for Roads Crossing Active Faults

In California, road design across active faults is informed primarily by Caltrans seismic and geotechnical guidelines. Caltrans applies a consistent strategy to surface-laid roads, it accepts localized damage at fault crossings and ensure corridor-level recoverability. Technical design is supported by geologic inputs from site-specific fault rupture studies guided by CGS Note 49 (Caltrans, 2022).

Defining Fault Deformation Zones - Caltrans requires surface-fault rupture analysis for any project within an Alquist–Priolo Earthquake Fault Zone or within 1,000 feet of a Holocene-active fault. Detailed trenching, mapping, and probabilistic displacement analyses are used to constrain the likely location and width of expected ground deformation. While no fixed width is prescribed, design teams typically define a corridor envelope that brackets both the primary rupture trace and potential secondary deformation across the length of roadway expected to experience fault rupture. Caltrans does not provide standard values, formulas, or envelope rules for road-specific deformation zones. The width and geometry are entirely based on site-specific investigations, interpreted by consultants and reviewed through the geotechnical design process. This leaves substantial variation between projects, with no prescriptive floor or ceiling.

Right-of-Way and Corridor Allocation – Right-of-way allocation refers to how Caltrans configures the horizontal and vertical geometry of the road corridor to accommodate rupture effects. If avoidance is not feasible, Caltrans expands the corridor at the fault crossing, sometimes adding shoulders or median space, to create a deformation zone within which damage can occur safely. Alignments may be adjusted to cross the fault nearly perpendicular, minimizing the length of affected pavement. These layout decisions are coordinated early in the project, ensuring space for post-event realignment and repair without encroaching on adjacent land uses (Caltrans, 2022). This strategy is supported in Caltrans planning-level documentation, but there is no formal method or required width increase derived from displacement size. Corridor expansion is left to design teams based on geometry and judgment. No tabulated values, thresholds, or spatial rules are provided.

Damage Localization and Repairability **-** Design measures in the faulting zone are focused on localizing deformation and facilitating rapid restoration. Caltrans typically defines a short sacrificial segment across the fault, where three primary strategies are applied:

- Pre-weakened pavement joints – These are deliberate discontinuities introduced in the pavement, typically perpendicular to the roadway centerline, and placed to align with the expected shear or extension direction across the fault trace. For predominantly strike-slip faults, this orientation helps isolate lateral shear within a defined band. For vertical displacement scenarios, joints may be located across fill transitions or embankment toes to allow for vertical separation without slab tearing. The joint itself may consist of a weakened section - thinner or with deliberately reduced adhesion - or a clean construction joint without dowels or keying. Their purpose is not to preserve continuity but to ensure that surface cracking initiates along these planes, simplifying damage inspection, limiting propagation, and enabling targeted resurfacing.
- Simplified structural layering – Pavement and subgrade layers in the faulting zone are built with reduced reinforcement or bonding to promote separation and reduce shear transfer. This approach accommodates both lateral slip and vertical steps, allowing differential movement without transmitting large stresses into adjacent pavement.
- Minimized buried utilities and surface features – Critical elements like ducts, lighting bases, and signage are excluded from the fault segment to prevent secondary damage and reduce post-event obstruction. Utility crossings, if unavoidable, are detailed for movement compatibility or rerouted outside the rupture zone.

Surrounding pavement zones are built stiffer or more continuous, creating a hierarchy where the sacrificial section absorbs the displacement a structural hierarchy, ensuring the sacrificial section absorbs the imposed ground displacement without propagating damage outward. The overall strategy resembles capacity design- protect the corridor's functionality by directing rupture effects into a planned, replaceable zone (Porter et al., 2023) Caltrans provides general principles and examples of sacrificial detailing, but these strategies are not codified in cross-section standards or technical memoranda for roads. Implementation depends heavily on engineering judgment, with no standardized sacrificial joint spacing, fault-parallel length, or detailing schema provided in manuals.

Post-earthquake goals for roadways prioritize quick reopening over undamaged performance. Repairs may involve regrading, fill replacement, or overlaying bridging plates. Caltrans emphasizes recovery logistics alongside design such as ensuring materials and access for emergency repairs are pre-planned. In past earthquakes, such as Landers (1992), highways were reopened within hours using these principles. Performance objectives are stated in terms of qualitative recovery expectations, not tied to explicit displacement or time-based design criteria. Caltrans does not define required restoration timeframes or pre-set performance levels for fault rupture in roads.

Embankment Behavior and Earthwork Strategy - Where roads cross faults on embankments, Caltrans uses the fill as a sacrificial buffer. Embankments may be widened or flattened near the fault to improve stability under deformation and for future realigning. Fill materials can be selected to promote controlled settlement rather than collapse. Reinforcements like geogrids are typically omitted or terminated at the faulting zone to avoid brittle transfer of fault movement. In essence, the earthworks are designed to absorb PGD without compromising the broader road prism (Caltrans, 2020).

These embankments also facilitate repair: deformed fill can be quickly cut, compacted, and repaved. This strategy mirrors high-speed rail practices in California, which call for embankment-based rupture absorption rather than structural resistance. These principles are practiced in projects and reflected in Caltrans geotechnical commentary, but not in the form of embankment-specific seismic design sections. No diagrams, soil strength ranges, reinforcement rules, or geometry-based displacement targets are codified. Designers are expected to define acceptable deformation and sacrificial behavior through site-specific modelling and peer-reviewed design reports

Assessment: Caltrans does not treat surface-laid roads as elastic nor resilient. Instead, fault rupture is accommodated through deliberate planning: define a deformation zone, allocate right-of-way to contain displacement, and detail sacrificial segments for fast, predictable failure and recovery. This strategy, supported by CGS-based rupture studies and formal design memos (Caltrans, 2013), ensures that road corridors retain functionality after rupture through managed degradation, not resistance. Overall, Caltrans provides strong conceptual support for fault-crossing road design, but codifies few quantitative design parameters. Implementation depends on consultant-led investigation, coordination with CGS, and project-level engineering decisions, with most fault-specific detailing remaining non-prescriptive.

FHWA

At the federal level in the USA, the Federal Highway Administration (FHWA) provides only limited technical guidance for at-grade road design across active faults. While seismic effects on highway infrastructure are broadly addressed in FHWA manuals, surface-fault rupture is only briefly acknowledged, and no formal standards exist for how to accommodate PGD in surface-laid roads. FHWA's position emphasizes hazard avoidance and broad resilience concepts but stops short of prescribing specific design methods or dimensions for fault-crossing segments.

Scope of Coverage and General Approach - FHWA recognizes that fault rupture is a localized and high-consequence hazard, and typically recommends route realignment where possible. Fault rupture is treated as a rare but potentially severe source of PGD, and the primary mitigation strategy is to avoid locating roads or embankments directly over active faults. Where avoidance is not feasible, FHWA guidance adopts a philosophy of accommodation, allowing fault displacement to occur in a controlled or repairable way, rather than attempting to resist it (FHWA, 2011).

Design Concepts for Accommodating Rupture - For surface-laid infrastructure crossing faults, FHWA describes just the one concept -Compressible materials in the deformation zone – An oversized excavation at the crossing may be filled with low-stiffness, soft, or loosely compacted soils that can deform under ground movement to absorb rupture-induced displacement. This sacrificial zone is intended to deform, localizing the offset and reducing stress transfer into adjacent pavement or subgrade.

However, FHWA does not extend these concepts to specific surface-layer design features. The guidance remains qualitative and depends on engineering judgment at the project level.

Absence of Prescriptive Criteria - FHWA does not define fault deformation zone widths, offset thresholds, or displacement compatibility limits for roadbeds. Designers are expected to evaluate the site-specific rupture hazard based on geological investigation, but the agency does not provide formulas or typical values to guide this process. No section of FHWA manuals establishes how much corridor length or width should be dedicated to accommodating rupture. Similarly, no drawing standards or pavement detailing instructions are included.

Assessment: FHWA's manuals offer only broad design principles for fault crossings and leave implementation details to local agencies and consultants. For surface roads, the federal approach is primarily conceptual, with no prescriptive standards or design requirements for accommodating surface rupture.

NZTA – New Zealand

In New Zealand, guidance for road corridors crossing active faults is issued by Waka Kotahi NZ Transport Agency (NZTA). While surface-fault rupture is recognized as a distinct hazard, NZTA provides no prescriptive design standards for surface-laid roads affected by PGD. The agency relies on project-specific investigation and functional recovery planning.

General Approach – NZTA acknowledges surface-fault rupture in its seismic guidance but does not include formal procedures for at-grade road design. When a fault crossing is unavoidable, the approach emphasizes early hazard identification, adjustment of alignment, and acceptance of local damage.

Design Concepts for Accommodating Rupture – Common design measures include:

- Unconsolidated fill in embankments to allow controlled deformation
- Fault-perpendicular alignment to minimize affected pavement length
- Avoidance of rigid elements across the fault trace
- Limited buried services, with flexible or rerouted alternatives
- Access for post-event inspection and repair

These strategies follow the logic of Concept B in Chapter 4.1: contain the damage, preserve corridor function, and enable rapid restoration.

Performance Objectives – NZTA does not define quantitative displacement limits or restoration times. Roads are allowed to crack or offset, provided function can be restored promptly by regrading or local repair.

Fault Investigation Requirements – Fault crossings require site-specific geologic investigation, including trenching and displacement scenario development. No fixed rupture width or offset values are given. These are determined through consultation with geotechnical specialists.

Prescriptive Status – NZTA provides no standard drawings or detailing requirements. Design expectations are set through hazard assessment and project-level decisions.

Assessment: NZTA does not codify fault-crossing design for roads. Its guidance relies on targeted investigation and damage-tolerant detailing, with repairability prioritized over resistance. Implementation is left to design teams based on local fault conditions and recovery needs.

Japan

In Japan, surface-fault rupture is recognized as a significant hazard, but no dedicated design standard exists for surface-laid roads across active faults. Formal guidance comes from national authorities including MLIT, the Japan Road Association, NILIM, and PWRI. These institutions issue technical reports and code commentary used in public projects, but most fault-crossing strategies are implemented through project-specific engineering instead of a mandatory standard.

Fault rupture is addressed in updated seismic bridge codes, but road-specific provisions remain limited. The general principle is to avoid active faults where possible. If a crossing is unavoidable, design must ensure that catastrophic failure is prevented and corridor function can be restored quickly *(Japan Road Association, 2017).*

Design Concepts for Accommodating Rupture – Japanese practice emphasizes deformation-tolerant, repairable solutions adapted to the site (JSCE, 2021). Typical strategies include:

- Loose fill in embankments to allow controlled deformation
- Fault-perpendicular alignment to minimize the affected length
- Avoidance of rigid elements such as continuous pavements or buried infrastructure
- Minimized buried services, rerouted or flexibly detailed where unavoidable

In addition, several strategies stand out as distinctive:

- Structural segmentation – Long structures such as walls or viaducts are divided into independently moving units, separated by joints or slip planes, to localize deformation and prevent progressive failure.
- Flexible sacrificial components – Pavement layers, bearings, or jointed elements are sometimes designed to yield or fail cleanly under fault offset, simplifying repair while protecting the surrounding structure.
- Inspection and repair access – Fault-crossing zones are designed with operational recovery in mind, including provisions for repair crew access, detour feasibility, and fast damage inspection.
- Performance Objectives – The design goal is not full continuity under rupture, but safe, localized damage with rapid restoration. Roads may deform or temporarily close, but must not collapse or become irreparable.
- Fault Investigation Requirements – Engineers are expected to use national fault maps and site-specific geological investigations to define rupture scenarios. There is no fixed displacement or zone width prescribed; each project tailors its approach based on expected ground movement.

Assessment - Japan's approach is formal but non-prescriptive. It emphasizes hazard recognition, damage localization, and restoration logistics, guided by public research institutions. Design solutions are project-specific, combining engineering strategies with operational planning to maintain corridor resilience.

Cross-Agency Synthesis: The diversity of guidance across countries reflects the uncertain and evolving nature of road design across active faults. Unlike pipelines, which follow a well-developed engineering workflow with broadly aligned standards, or structures, which often lack fault-specific codes entirely, surface roadways occupy a middle ground. Here, national agencies apply Concept B strategies in varied ways—some codify sacrificial zones and corridor-level recovery (Caltrans), others outline general principles with little technical prescription (FHWA, NZTA), while some, like Japan, rely on project-based engineering informed by public research but without uniform standards. The result is a wide spectrum of design measures, from embankment detailing and alignment rules to segmentation and operational recovery planning. This variability highlights the challenge of reconciling fault rupture hazards with surface infrastructure that is long, exposed, and difficult to harden—but also inherently restorable.

4.4.2 Academic and Analytical Approaches

Beyond the largely qualitative agency guidance summarised above, academic literature provides the analytical and empirical basis for why sacrificial zoning and rapid restoration dominate road–fault practice. In the academic approach, unlike structural or buried infrastructure, roads are typically assessed based on how quickly they can return to usable condition following surface rupture. Recent resilience-oriented work on lifeline infrastructure has emphasized that post-earthquake performance should be assessed not only by physical damage, but also by loss of functionality, service disruption, and recovery time (NIST, 2024; Poulin and Kane, 2021).

Crossing orientation – widely acknowledged in literature as a geometric tool for reducing fault-induced damage footprint. A near-perpendicular alignment shortens the rupture-affected road segment and simplifies repair logistics. Its benefit applies across all fault types, and it is often used alongside embankment or sacrificial segment strategies.

Deformation-tolerant embankments - are consistently identified as an effective and adaptable solution. Case histories show that embankments constructed with unconsolidated or lightly compacted fill deform in a distributed way under ground offset, concentrating damage in predictable locations while preserving the broader road prism. Analytical work and field studies across multiple earthquakes support the view that such embankments can tolerate meter-scale displacements without total loss of function, and are often the fastest to restore. After the 7.8 Mw Kaikōura earthquake in New Zealand and the 7.0 Mw Kumamoto earthquake in Japan, both in 2016, damaged road sections crossing faults were frequently reopened within days using basic earthmoving and patching, largely because the embankments had absorbed rupture effects without causing system-wide failure. Several modeling studies and field back-analyses suggest that this approach achieves a favorable balance between cost, expected damage, and recovery time, particularly when compared to rigid structural alternatives or over-designed foundations (Bray and Macedo, 2017; Loli et al., 2020).

Sacrificial pavement segments – are frequently proposed as a means to concentrate surface rupture effects within short, preselected road sections. These segments are detailed to crack or offset along known fault traces using construction joints, thinner pavement layers, or simplified structural profiles. The aim is not to preserve surface integrity, but to allow damage in a controlled, repairable form. Case evidence supports this: after the 7.8 Mw Kaikōura earthquake and the 7.0 Mw Kumamoto earthquake, faulted pavements were repaired rapidly, often with basic regrading or patching, because damage was confined to predictable zones of rupture. Observational studies and idealized modeling show that sacrificial segments, when placed correctly, can limit disruption to the surrounding corridor and reduce post-event inspection and repair scope (Bray and Oettle, 2009). Their effectiveness is highest when fault location is well-constrained and the rupture width is narrow enough to target within a single defined crossing zone.

Structural segmentation – is occasionally applied in road corridors where continuous structures, such as long retaining walls or viaduct-like segments, cross active faults. By dividing these elements into independent units with slip joints or separations, fault-induced displacement is localized and prevented from propagating through the entire structure. While well established in bridge and rail design, its relevance to surface roads is limited, except where rigid, tied structures are embedded along the corridor (Nishida et al., 2019; JSCE, 2021).

Designing for rapid restoration – is emphasized in several post-earthquake evaluations as a key enabler of resilience and a practical strategy for minimizing seimsic downtime risk of the network. Design measures that support early inspection and access have been shown to reduce service disruption significantly, such as widened shoulders, simplified geometry at the faulting zone, or pre-positioned materials, After the Kaikōura and Kumamoto earthquakes, road sections with accessible fault crossings were repaired within days, while those in constrained or complex terrain faced longer closures. Field reports and recovery planning studies consistently highlight that even modest, design-stage decisions can substantially improve post-event response time (Mason et al., 2017; World Bank & GFDRR, 2012; MLIT, 2016; Aghababaei et al., 2021).

Flexible components and displacement-tolerant detailing – are used selectively to accommodate fault-induced movement without causing brittle failure. Examples include ductile joints in retaining systems, flexible support details in surface-mounted equipment, or slip interfaces in rigid roadside structures. While more commonly associated with bridges, literature suggests that such detailing can reduce damage concentration and simplify post-event repairs when integrated into fault-crossing segments. Their effectiveness depends on clear fault trace identification and displacement estimates, and is most useful where rupture is narrow and predictable (Loli et al., 2020).

Network redundancy and fault avoidance – represent the two main macro-level approaches to managing fault rupture risk across transportation corridors. Redundancy involves ensuring that alternate routes or parallel links exist, so that a fault rupture at one location does not isolate critical access. This is often achieved through spatial planning, route hierarchy, or emergency detour provisioning, and is widely cited in Japanese and New Zealand literature as essential to post-disaster mobility. In contrast, fault avoidance aims to eliminate rupture exposure altogether through alignment shifts. While theoretically the most effective measure, it is frequently infeasible due to topographic, environmental, or land use constraints. Studies suggest that redundancy offers a more scalable and flexible approach, particularly where fault location is uncertain or avoidance would significantly compromise network function (Aghababaei et al., 2021; MLIT, 2016; World Bank & GFDRR, 2012; Mason et al., 2017; Medard, 2000).

4.4.3 Fault-Rupture Investigation for Roads with Sacrificial Design

For sacrificial road design strategies to be technically defensible, the expected rupture location, deformation-zone width, and displacement direction must be constrained to a level that justifies concentrated detailing. These constraints derive from site-specific fault investigations and determine the confidence with which a segment can be designed as a sacrificial detail or physically isolated.

The required input level depends on the detailing strategy applied. Broadly:

- Mapped fault trace and displacement sense support basic corridor planning and route alignment.
- Trenched fault geometry and rupture typology inform the expected rupture expression and help define whether fault crossing is necessary or avoidable. They also guide crossing orientation and corridor layout. For example, crossing at near-perpendicular angles, or allocating wider shoulders to accommodate realignment.
- Deformation-zone width is required to justify how wide the sacrificial design zone must be. This includes both the primary rupture and the area of distributed surface deformation.

- Soil cover properties and secondary cracking patterns affect the location and extent of weak points, embankment transitions, or surface jointing strategies.

Where deformation is expected to spread across a distributed shear zone, or where multiple secondary traces are present, the sacrificial segment must be widened accordingly. Without data on the external limits of rupture-related cracking, designers must apply buffers to accommodate large uncertainty. However, if the width is overestimated, land use or cost constraints may become critical.

Fault type plays a key role: strike-slip ruptures often produce narrow, linear shear bands, while reverse or normal faults may cause broader uplift, settlement, or scarping. These patterns affect embankment geometry, joint spacing, and repair planning. Thus, trenching and surface investigations must aim to define:

- The location and spatial uncertainty of the primary surface rupture
- The faulting mechanism and expected displacement direction
- The relationsheep between PGD magnitude and exceedance probability
- The general area over which surface deformation may occur
- The occurrence, density, and pattern of secondary surface ruptures

Where these parameters are poorly constrained, design conservatism must increase, either by widening the sacrificial zone or selecting higher-tolerance solution. These inputs define whether embankments, joints, or geometry adjustments can be justified as focused rupture accommodation.

4.4.4 Conclusion

The engineering treatment of roads crossing active faults is defined by the acceptance of localized damage and the prioritization of recoverability- an approach consistent with the sacrificial zoning philosophy outlined in Concept B in chapter 4.1. Unlike component-based systems, road corridors are typically designed to tolerate rupture at a defined segment and to enable restoration shortly after an event. The literature reveals a relatively mature body of knowledge in this area, built not only from analytical studies but also from repeated post-earthquake observations. Earthquakes have demonstrated how surface-laid roads perform across different rupture types and terrains, and how well-placed sacrificial elements can limit disruption and enable rapid re-use. As a result, multiple design strategies have been implemented and tested in real-world events, giving engineers a broad toolkit of detailing strategies and layout options.

This experience also leads to diversity. National and agency-level guidelines prescribe differing fault-crossing solutions, some formalized in codes, others left to designer judgment. While the core principle of controlled, localized damage remains stable, its application varies in the details. How wide to build the deformation zone, how much to simplify pavement layers, how to shape the embankment, or whether to segment roadside structures. These decisions depend not only on hazard characterization but on how well the site-specific fault behavior is understood. Fault type, rupture geometry, and secondary cracking patterns all influence the design envelope. In this context, site investigation plays a dual role. It defines the input parameters for sacrificial detailing, but also frames the uncertainty bounds within which such detailing remains valid. Design can accommodate some spatial imprecision, but it cannot proceed blindly. Uncertainty accommodation changes with each solution type.

While the design philosophy of sacrificial zoning is well accepted and technically mature, its codification remains fragmented. Existing standards outline possible tools, but rarely prescribe which approach is appropriate under which conditions. The logical next step for guidance development is not the invention of new strategies, but the structuring of existing ones. Clarifying when embankment-based absorption is preferable to pavement segmentation, or when widening the corridor is more defensible than structural detailing. As practice continues to evolve, particularly in high seismic regions, future codes may need to evolve from endorsing broad principles to recommend context based applications according to fault behavior and corridor function to minimize cost and seismic risk.

4.5 CONCLUSION

This chapter examined the engineering feasibility and limitations of constructing buildings and infrastructure over active faulting zones. It uses three representative asset classes, ordinary buildings, buried pipelines, and road corridors, to illustrate the core response concepts for construction in fault-rupture zones. The three approaches presented are rigid body mechanism tolerance, displacement compatible detailing, and sacrificial zoning with rapid recovery. Although each system interacts with fault rupture in a distinct way, several unifying conclusions emerge that define the current boundary of engineering knowledge, practical design and realistic future practice.

A first common principle is that surface-fault rupture is a PGD hazard, whereas most code based seismic design procedures are fundamentally force based. Standard seismic provisions primarily address shaking by translating ground motion into inertia related actions and verifying performance through strength and ductility. Surface rupture, however, imposes permanent relative displacement across the faulting zone and therefore creates an incompatibility problem rather than a force demand problem. As a result, the design emphasis shifts toward deformation tolerance, continuity, and soil structure interaction, while conventional force -based solutions are generally not relevant to this type of hazard. The three response concepts presented in this chapter can therefore be understood as alternative ways to manage geometric incompatibility under imposed ground deformation in order to achieve different performance objectives.

Second, the feasibility of any fault-rupture design strategy depends critically on the quality of the site -specific fault investigation. As shown in Chapter 3, uncertainty in rupture location, deformation zone width, and displacement directionality governs which mitigation pathways are technically rational.

- Rigid-body tolerance can operate under relatively broad uncertainty, since isolated continuous foundations can absorb relative deformation and redistribute support without relying greatly on precise rupture location and directionallity.
- Sacrificial zoning for road corridors requires moderate precision, enough to localize damage within a designated segment.
- Displacement-compatible detailing requires the highest precision, because strain limits depend directly on displacement location, magnitude and direction.

In all cases, the absence of reliable geological input imposes larger, more conservative design envelopes. Conversely, better constraint on rupture geometry and displacement magnitude enables more focused and cost-effective solutions.

Third, codification in formal design codes remains very limited across all three asset classes, and where it exists it rarely matches the displacement governed nature of fault rupture. For ordinary buildings, code provisions are mainly framed as avoidance statements or investigation triggers, with little or no guidance on displacement compatibility, acceptance criteria, or verification procedures. For pipelines, Eurocode provisions provide strain limits and prescriptive placement measures, but still do not establish a complete workflow for defining displacement demand and verifying performance in a consistent, performance based manner. For surface road corridors, code level treatment is essentially absent, which forces design to rely on project specific engineering decisions and recovery planning rather than standardized code checks. As a result, the practical engineering response to fault rupture is not constrained by a mature code methodology but by a combination of site investigation quality, project consequence, and the availability of specialized sector practice and guidlines that can fill the code gap.

Fourth, the three exemple systems reveal distinct yet complementary engineering pathways:

iv) Ordinary buildings can feasibly adopt rigid-body mechanism tolerance through robust rafts or box foundations, accepting rotation and serviceability loss while preserving life safety. These strategies do not eliminate damage may surve life safety amd collapse prevention under realistic displacement demands. For public importance structures, base isolation and other types of technology may serve even higher performance criteria.

v) Buried pipelines must be designed through explicit displacement-compatible detailing, using strain-based acceptance criteria and nonlinear soil–pipe interaction models. This is the most advanced and codified domain, demonstrating that displacement-based design is possible when supported by clear performance objectives.

vi) Road corridors are commonly treated through sacrificial and recovery-focused zoning, where controlled damage and rapid post-event reinstatement are the dominant performance objectives. This approach reflects both economic rationality and the intrinsic geometry of linear, ground-coupled systems.

Finally, this chapter highlights that design for surface-fault rupture is fundamentally an exercise in managing uncertainty. Some uncertainty is irreducible because rupture rarely manifests as a single deterministic line at the site scale, yet engineering decisions can still be structured rationally when uncertainty is stated explicitly and carried through the design logic. Where uncertainty remains high and consequences are severe, avoidance is often a defensible strategy. Where consequences are moderate and site investigation can reduce uncertainty in fault location and deformation extent, tolerance -based design becomes feasible and can be justified as a rational risk management approach.

5.Thesis conclusion

Seismic engineering practice is highly codified for ground shaking, but remains weakly codified for surface fault-rupture, despite the fact that rupture may control performance at the site scale. Unlike shaking, which is commonly represented as inertia-related actions, surface rupture imposes permanent relative displacement across a faulting zone and therefore poses a compatibility problem rather than a force-resistance problem. The engineering emphasis consequently shifts toward deformation tolerance, continuity, soil-structure interaction, and clearly stated performance objectives. An appropriate approach therefore begins by defining performance in practical terms - what stability, recoverability, and functionality mean for different assets, and only then selecting a response logic that matches those objectives.

This thesis is intended as a synthesis of the current state of practice and knowledge on construction in active fault-rupture environments, rather than as a proposal of a new design method. By bringing together what is available across codes and regulations, guidance documents, academic research, and major projects, it consolidates how surface fault-rupture is currently addressed and what engineering options are realistically supported. The discussion focuses on ordinary buildings, buried pipelines, and road corridors as three representative asset classes, chosen to examine broader patterns and constraints beyond these cases.

Within that performance framing, the engineering options that emerge across the literature can be organized into a small set of recurring response logics. One logic is rigid-body tolerance, where the primary aim is to protect the superstructure's stability and life-safety by driving a coherent foundation response that reduces damaging differential distortion, even if this results in permanent rotation, settlement, and loss of operability. A second logic is sacrificial deformation zoning with recovery-focused planning, which accepts that localized damage and loss of serviceability will occur within a defined corridor, but aims to control where that damage concentrates and to enable rapid reinstatement after the event. A third logic is displacement-compatible detailing, where fault-rupture is treated explicitly as an imposed deformation demand and performance is verified through deformation-based acceptance criteria correlating with the performance goals. These three logics are not confined to the particular asset examples discussed in the thesis; they are a concise way to describe how engineering can engage with PGD hazard across a wider set of structural systems, while keeping the selection of a response anchored to the intended performance objective and the realities of what can be achieved in practice.

When the different response logics are compared, a clear difference emerges in their susceptibility to uncertainty. Surface rupture is rarely known at project scale as a single deterministic line with a single displacement value; instead, the fault trace is better treated as a location envelope, deformation may be distributed across a finite shear band, and both displacement magnitude and directionality can control the governing mechanism. Some response concepts can still function when rupture location is constrained only to a corridor, precisely because they do not depend on predicting an exact emergence line and instead seek to protect the superstructure through a coherent system response that can tolerate a range of possible deformation locations. Other concepts become more sensitive as spatial uncertainty increases, because their effectiveness depends on bounding where deformation is likely to concentrate so that damage can be intentionally localized within a defined, repairable zone rather than spreading into critical components. The most demand-specific approaches are the most exposed to uncertainty. Where performance is verified against deformation-based acceptance criteria, the design becomes directly sensitive to the assumed displacement magnitude and directionality, so uncertainty in those inputs propagates immediately into feasibility, detailing requirements, and the credibility of the verification itself. For this reason, uncertainty is treated in this thesis as a thread that connects hazard characterization, investigation effort, and the rational selection of engineering solution.

Once uncertainty is recognized as a constraint, the discussion shifts to what information can realistically support the engineering approach. The most beneficial site-investigation outputs are those that constrain the deformation problem in engineering terms: the positional envelope of the fault relative to the project footprint, the likely width and distribution of surface deformation across the shear band, credible displacement components and directionality, and the shallow fault-zone and cover conditions that influence whether rupture localizes or diffuses as it approaches foundation level. Without these constraints, design strategies cannot be justified with confidence. With them, engineering choices can be framed transparently in relation to risk-management objectives and the residual uncertainty that remains.

Building on these information needs, the thesis evaluates the main site-investigation methods in terms of the distinct information each can deliver and the degree to which it can confine uncertainty at project scale. This synthesis is then used to propose investigation levels whose scope increases with project importance and with the performance objective that the design is required to meet under fault-rupture uncertainty.

Regulations often acknowledge surface fault-rupture indirectly by triggering a site-specific investigation when a project falls within a mapped fault zone or a suspected trace, yet they rarely specify in practical terms what the investigation must achieve, what level of precision is expected, or how uncertainty should be reported and carried into decision-making. Where the engineering practice is not consolidated into repeatable guidance and verification steps, this gap leaves regulators with limited defensible options beyond enforceable siting controls, so avoidance, setbacks, and prohibitions become the dominant risk-management tools. Avoidance is therefore not necessarily practiced because it is always the most beneficial outcome, but because it may become the only active risk-management decision available when credible mitigation and verification procedures are not established.

The cross-jurisdiction comparison in this thesis examines how five systems (Israel, California, Turkey, Taiwan, and New Zealand) manage surface fault-rupture as a risk-management problem through planning controls. The comparison considers how fault zones are defined and mapped, what triggers site-specific investigation, how setbacks and prohibitions are applied, and how pre-existing development is treated. It shows that jurisdictions settle on different balances between prohibition, flexibility, and procedural control, reflecting their institutional settings and the degree of existing exposure in fault corridors. Disaster-driven frameworks tend to institutionalize strong avoidance language but often operate procedurally in built environments, whereas planning-law frameworks more explicitly modulate controls by context and consequence. Code-embedded approaches can be nationally uniform yet less adaptable to local economic and urban realities.

Avoidance is therefore best understood as one risk-management option within a broader decision space. It can be highly effective at reducing future exposure by preventing new assets from being placed directly within faulting zones where the hazard is highest, but it is not automatically the most beneficial outcome in every setting. In already built-up corridors, strict avoidance rules can produce the "freeze" effect discussed in this thesis, where locations with the highest inherited hazard remain occupied while renewal, strengthening, or redesign becomes difficult to pursue, leaving risk essentially unchanged. The question is not whether avoidance is right in principle, but when it truly reduces overall risk under prevailing conditions and uncertainty.

Future progress in this field depends less on inventing new concepts and more on codifying and consolidating what is already known into repeatable methods that regulators can rely on without defaulting to prohibition. Uncertainty is the common thread linking hazard characterization, investigation effort, performance objectives, and feasible response logics. If guidance is made sufficiently clear and repeatable - especially for routine private-sector development where strict avoidance is not clearly optimal yet full displacement verification is not typically supported - regulatory systems gain a practical alternative to avoidance-by-default, and can adopt more nuanced, performance-anchored decisions without losing enforceability.

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