Pipeline Failure due to Soil Instability
A Global Overview, Case Study, and Advanced Monitoring Technologies

Source: Drone footage from Selangor Fire and Rescue Department / Media coverage of the Putra Heights gas pipeline explosion (April 1, 2025)

Prepared for Industry Review
July 2025

Authored by:
Christopher Do (CTO – IEV) and Dr. E.S. Lim (CBS – Aerodyne)

Table of Contents

1.0 Abstract

Pipeline infrastructure is vulnerable to geotechnical hazards that can undermine structural integrity and lead to catastrophic failures. This paper provides a comprehensive overview of pipeline failures caused by soil instability around the world, with engineering-level analysis of failure mechanisms.

A detailed case study of the April 2025 Putra Heights gas pipeline explosion in Malaysia is presented, incorporating official findings from the Department of Mineral and Geoscience (JMG) and Department of Occupational Safety and Health (DOSH). The case study illustrates how gradual ground settlement and water-saturated soil conditions induced cyclic stresses and strain-induced cracking in a high-pressure gas pipeline, resulting in a massive explosion.

The geotechnical and structural failure mechanisms – including ground subsidence, soil saturation, loss of support, fatigue, and tensile overload – are analyzed in depth. Preventive strategies and technologies are then discussed, with special emphasis on Skipper NDT, a drone-based magnetic mapping and bending strain assessment platform that enables non-contact detection of pipeline movement. A comparative review of advanced early warning and monitoring technologies is provided, including distributed strain sensing (DSS) fiber optics, satellite interferometric radar (InSAR), ground penetrating radar (GPR), UAV-based LiDAR surveys, SCADA system integration, and digital twin modeling. A comparison table highlights the capabilities and limitations of these technologies for detecting underground pipeline threats.

The study concludes with recommendations for integrating multi-faceted monitoring systems – combining geotechnical data, real-time sensors, and digital twins – to proactively manage soil instability risks and enhance the resilience of pipeline networks. Industry professionals will gain a clear understanding of the failure processes involved in pipeline–soil interactions and the state-of-the-art tools available to predict and prevent such failures.

2.0 Introduction

Pipelines form the backbone of global energy and utility networks, transporting oil, gas, and water across vast distances and varied terrains. Ensuring their integrity is critical, yet soil instability poses a persistent threat to buried pipelines. Ground movements such as landslides, subsidence, and erosion can impose abnormal loads on pipelines, leading to deformation or rupture. Around the world, there have been numerous incidents where geotechnical failures have precipitated pipeline disasters. For example, a catastrophic landslide in Shenzhen, China in 2015 ruptured natural gas pipelines, causing massive leaks, fatalities, and disrupting gas supply to Hong Kong. In 2016, heavy rains triggered a landslide in Hubei Province that ruptured the West–East Gas Pipeline, resulting in an explosion. Similar hazards have affected pipelines in mountainous or unstable regions; the China-Myanmar gas pipeline experienced multiple rupture incidents due to landslides in 2017 and 2018. Even in North America, geohazards have caused pipeline failures – a landslide led to an oil pipeline spill in North Dakota in 2016, and shifting saturated soil caused a CO_2 pipeline rupture in Mississippi in 2020. These cases underscore that soil instability is a global challenge, not confined to any one region or pipeline system.

From an engineering standpoint, the interaction between buried pipelines and moving soil is complex. As the ground shifts, it can bend, buckle, or shear a pipeline, potentially exceeding the material's strain capacity. Pipelines are usually designed to withstand internal pressure and some external loads, but sustained or cyclic ground deformation can introduce significant axial and bending stresses. If the supporting soil beneath a pipeline settles or erodes, sections of the pipeline may become unsupported, creating spans that sag under their own weight. Repeated cycles of loading as the pipeline moves can initiate fatigue cracks. Eventually, a critical loss of structural integrity can occur, resulting in leaks or sudden ruptures. Industry investigations have often found that pipeline ruptures in unstable ground tend to occur at welded joints or other stress concentrators, where the material experiences the highest combined stresses. Recognizing these failure mechanisms is crucial for developing effective monitoring and mitigation strategies.

This paper explores pipeline failures due to soil instability through both a broad lens and a specific case study. The Putra Heights gas pipeline explosion in Malaysia is examined in detail as an illustrative example of how long-term ground settlement and saturation can culminate in a catastrophic failure. We then review current literature and practices concerning pipeline geotechnical hazards, and identify advanced technologies that enable early detection of the precursors to such failures. The aim is to equip industry professionals with a clear understanding of (i) the geotechnical and structural processes that lead to pipeline failure, and (ii) the state-of-the-art tools – from fiber-optic strain sensors to satellite monitoring and drone-based surveys – that can be deployed to monitor pipeline corridors and prevent disasters. In doing so, we emphasize an integrated approach that combines multiple data sources (geological, sensor-based, and operational) into proactive pipeline integrity management, including the promising integration of Skipper NDT's drone-based magnetic mapping platform for detecting pipeline strain. The subsequent sections present a literature review of pipeline–soil interaction failures, the methodology of our case analysis, the detailed case study of Putra Heights, a discussion of failure mechanisms, an overview and comparison of advanced monitoring technologies, and finally recommendations for industry application.

3.0 Literature Review: Pipeline Failures and Soil Instability

Pipeline integrity issues arising from soil instability have been documented in many regions, prompting extensive research into pipeline–soil interaction and geohazard management. Buried pipelines are continuously subjected to forces from the surrounding soil, and when the ground moves, those forces can increase dramatically. Landslides are a primary concern – studies note that landslide-induced pipeline failures often result in full-bore ruptures rather than small leaks, due to the large mass and forces involved. In a notable analysis of a CO_2 pipeline rupture in Satartia, Mississippi (2020), investigators concluded that "the failure of the pipeline was a result of soil movement which caused excessive axial loading leading to failure at the girth weld," after heavy rains saturated the hillslope. The wet, loosely consolidated loess soil lost stability and slumped, applying bending and tensile forces that snapped the pipeline. This case also revealed that the pipeline operator had experienced minor land movement incidents along the route two to three times per year, indicating a chronic geohazard issue. U.S. regulators, recognizing the risk, had issued guidance (e.g. PHMSA Advisory Bulletin ADB-2019-02) alerting operators to monitor for geological hazards and mitigate them.

Beyond landslides, land subsidence and settlement have emerged as insidious threats, especially in areas of soft or compressible soils. Subsidence can occur due to natural consolidation, groundwater extraction, mining, or long-term soil wetting. A slowly settling ground may not grab headlines like a sudden landslide, but it can progressively deform a pipeline over months or years. If a pipeline is restrained at fixed points (e.g., by anchor blocks or rigid connections) while the ground between sinks, the pipe is forced to bend. This was precisely the scenario identified in the Putra Heights case, where decades of gradual settlement resulted in a section of pipeline sagging and losing continuous support. Studies modeling pipeline response to subsidence show that axial and bending strains accumulate and can eventually exceed the steel's yield strength, especially at welded joints or bends where stress concentrates. Cyclic settlement – for instance, seasonal swelling and shrinking of clays, or repeated wetting and drying – can introduce fatigue loading. Metallurgical examinations of failed pipelines often reveal fatigue striations on fracture surfaces, indicating crack growth under fluctuating stress before final rupture.

Another mode of soil instability is erosion or scour, which can create voids beneath pipelines (for example, at river crossings or due to flash floods). If a pipeline span becomes unsupported over a void, it behaves like a free beam and may buckle under its own weight or internal pressure. Such free-span buckling can be followed by a fracture. Also, soil liquefaction during seismic events can temporarily remove support and impose large deformations on pipelines. In seismically active and permafrost regions, pipeline designers have adopted strain-based design approaches to accommodate some ground movement, but unexpected excessive movement can still overwhelm a pipeline's ductility.

Globally, pipeline operators and researchers have been developing frameworks for geohazard management. Best practices involve identifying susceptible areas (e.g. mapping landslide-prone slopes, active faults, and soft soil zones) and implementing monitoring. The Interstate Natural Gas Association of America (INGAA) has published guidelines on managing ground movement hazards, emphasizing site surveys and surveillance. In recent years, advanced remote sensing has been applied: for instance, satellite InSAR has been used to detect millimeter-scale ground subsidence along pipeline corridors. In one case, InSAR monitoring in the Groningen gas field (Netherlands) tracked ground subsidence due to gas extraction and helped operators adjust pipeline operating pressures. Fiber-optic distributed sensing is another emerging tool, allowing strain, temperature, and vibration to be measured continuously along the length of a pipeline by using the fiber itself as a sensor. Research at UC Berkeley and elsewhere has demonstrated that distributed fiber strain sensing can detect ground movement impacts on pipelines in real time, potentially providing early warning of deformation before a rupture occurs. Several pilot projects have successfully integrated fiber-optic cables with pipelines to monitor for strain accumulation, thermal anomalies (leaks), and even third-party interference, feeding data into pipeline SCADA systems for real-time alerts.

In summary, the literature indicates that geotechnical factors are a leading external cause of pipeline failure, alongside corrosion and third-party damage. Key insights include: (1) Unstable slopes and sinking ground can impose excessive tensile or compressive strains on pipelines, often manifesting at welds or bends. (2) Failures due to soil movement typically develop over time (slow accumulation of strain) but can culminate in sudden ruptures, combining both time-dependent fatigue and overload. (3) Early detection is possible using modern sensing technologies – e.g. satellites to watch the ground, and fiber sensors to watch the pipeline – which can greatly improve an operator's ability to intervene (by pressure reduction or shutdown and repair) before a leak or explosion happens. These lessons from global experience set the stage for examining the Putra Heights incident in detail, and for discussing how advanced monitoring techniques might avert similar disasters in the future.

4.0 Methodology

This research adopts a multi-pronged methodology combining case study analysis, forensic data review, and technology assessment. First, a case study approach is used to delve into the Putra Heights pipeline explosion – one of the most significant pipeline failure incidents linked to soil instability in recent years. Official investigation reports and press releases from Malaysian authorities (DOSH, JMG, and related agencies) were collected and analyzed to extract key findings on the failure cause, geotechnical factors, and damage outcomes. Engineering details such as measured soil settlement, pipeline displacement, fracture characteristics, and metallurgical evidence were compiled from these sources. Eyewitness accounts and news reports (e.g. from *The Star*, Bernama, and *The Edge Malaysia*) were also reviewed to capture the timeline of events and the impact on the surrounding community.

Next, a forensic analysis was conducted by synthesizing the reported data to reconstruct the failure mechanism. This involved interpreting soil investigation results (bearing capacity, moisture content, presence of water tables) alongside pipeline stress analysis concepts. We considered the pipeline's operational history (25 years of service) and the environment (urban development, drainage patterns, climate factors) to identify why the soil conditions deteriorated under the pipeline. The methodology mirrors the investigators' approach: on-site inspections, laboratory testing of failed pipe samples, and computer simulations were all part of the official investigation. We use their outcomes (e.g. location of fracture at a girth weld, evidence of cyclic stress patterns, and calculations of soil subsidence) to support our analysis of how the failure progressed.

For the technology review and comparison, we performed a literature search and product survey of current and emerging pipeline monitoring techniques. Technical white papers, industry journals, and product datasheets were reviewed for each technology: Distributed Strain Sensing (DSS) via fiber optics, InSAR satellite monitoring, Ground Penetrating Radar (GPR) surveys, Unmanned Aerial Vehicle (UAV) LiDAR mapping, pipeline SCADA integration, digital twin modeling, and drone-based magnetic mapping (Skipper NDT). The capabilities of each were assessed in terms of what parameters they monitor (e.g. ground movement, pipeline strain, leakage, etc.), spatial and temporal coverage, precision, and limitations such as environmental constraints. Where possible, documented case studies of their usage in pipeline contexts were included (for instance, InSAR being used for landslide monitoring on pipeline rights-of-way, or fiber optics detecting ground subsidence impacting a pipeline). Skipper NDT was given special focus: we examined its drone-borne magnetometer approach to map pipeline position and stress state, referencing field trials and deployments by major operators.

Finally, we consolidated the findings into a comparison table to juxtapose these technologies in a structured manner. The criteria for comparison include detection principle, types of threats detected (ground movement, deformation, leak, etc.), advantages (such as coverage or real-time capability), and limitations (such as cost or need for installation). All information is cited from authoritative sources or official documentation to ensure accuracy. The recommendations formulated at the end are based on cross-analysis of the case study lessons and the capabilities of the monitoring technologies reviewed. By following this methodology, we ensure that our conclusions are grounded in both the real-world evidence of a failure and the proven performance of preventative tools.

5.0 Case Study: Putra Heights Gas Pipeline Explosion (Malaysia, 2025)

On April 1, 2025, a high-pressure natural gas pipeline exploded in the suburban neighborhood of Putra Heights, Subang Jaya (Selangor, Malaysia), causing one of the country's worst industrial disasters. The 36-inch diameter underground pipeline, operated by Petronas Gas, had been in service since 2000, supplying gas across Peninsular Malaysia. That morning, at approximately 8:08 a.m., residents were jolted by a thunderous blast and a raging fireball in their community. The ensuing inferno, fueled by escaping gas, sent flames soaring over 30 meters high – some eyewitness accounts said hundreds of meters, forming a mushroom-shaped fireball visible from kilometers away. The heat was intense, reportedly reaching up to 1000 °C near the crater, and it ignited homes and vehicles in the vicinity. It took firefighters nearly eight hours to fully extinguish the blaze. Miraculously, no fatalities occurred, but the toll on the community was severe: about 150 people suffered injuries ranging from burns to smoke inhalation. Over 80 houses were completely destroyed and at least 140 more were damaged or rendered unsafe. The explosion carved out a crater approximately 9.8 m deep at the epicenter, and sent debris flying across a wide radius.

Image source: Faihan Ghani / The Star (Malaysia), published in "No foul play in Putra Heights pipeline explosion," July 1, 2025.

In the immediate aftermath, attention turned to the cause of this disaster. Given the timing (during a major public holiday) and scale, early speculation ranged from accidental damage by nearby construction to sabotage. However, a thorough investigation led by DOSH (Occupational Safety and Health Department) in collaboration with JMG (Mineral and Geoscience Department), the Public Works Department (JKR), the Fire and Rescue

Department (JBPM), and the police ruled out foul play. At a press conference on June 30, 2025, DOSH officials announced that the explosion's cause was firmly identified as **soil instability** – essentially, the ground under the pipeline had given way over time. The pipeline section that failed was located beneath a monsoon drain in a residential area, and investigations revealed that this drain area had a history of poor soil conditions. Over the 25 years since pipeline installation, the soil had settled significantly. Precise surveying showed 24.3 cm of vertical land subsidence at the failure location. Correspondingly, the pipeline itself had shifted and sagged by about 15.9 cm out of alignment. Effectively, the bottom portion of the steel pipe was no longer firmly supported by soil – an air gap or void existed under parts of it, due to the soft ground subsiding unevenly.

Soil samples taken by JMG painted a picture of the subsurface environment: the soil was found to be waterlogged and unusually soft. The area sits on former marshy land, and investigators discovered natural underground water reservoirs in the soil strata. Years of water accumulation (likely exacerbated by heavy rains and inadequate drainage) had caused the clayey soil to lose strength – essentially turning into a mud-like consistency. The bearing capacity of such saturated soil dropped to the point that it could not support the weight of the pipeline above, especially when the pipeline was filled with pressurized gas (adding weight and stress). Notably, the monsoon drainage structures in the area and nearby culverts were also affected by the ground softening – there were signs of differential settlement around these structures. This indicates that the issue was not isolated to the pipeline itself but was a broader geotechnical problem in the vicinity.

The pipeline's structural response to this gradual loss of support was a critical part of the failure. As the ground settled away from the pipe, a span of the pipeline became suspended, creating a bending deformation in the steel. Each time gas flowed or pressure cycles occurred, the pipe likely moved slightly, vibrating or deflecting under its own weight. DOSH's Petroleum Safety Division Director described this as repeated **cyclic loading**: the pipeline would flex downward into the soft pocket and spring back, again and again. Over months and years, such cyclic loading can induce metal fatigue. Indeed, laboratory metallurgical analysis of the failed pipe segment (samples of which were sent to SIRIM for testing) confirmed the presence of fatigue striations on the pipe's interior surface – telltale microscopic lines indicating progressive crack growth due to fluctuating stress. The crack had initiated likely at the welded joint in that pipeline section, since welds can be slightly more rigid or contain minor flaws, making them common points for failure under stress.

Eventually, the crack reached a critical size. The investigators concluded that a **tensile overload** event was the final trigger for rupture – essentially, the pipe experienced a stress beyond its yield and fracture point, causing it to tear open suddenly. This was characterized as a ductile failure, meaning the steel deformed significantly (with visible necking and elongation at the break) before parting, which is consistent with an overload scenario. Once the pipe ruptured, high-pressure natural gas (odorless and colorless) gushed out into the surrounding soil and along the drain. Something ignited the gas cloud moments later – possibly a spark from rocks scraping, or an electrical source – causing the massive explosion and fire.

The devastation in the neighborhood was extensive. *Entire rows of terrace houses were reduced to charred shells.* Official tallies indicate 237 houses were affected by the fire, with 88 structures (78 houses and 10 shoplots) burned between 40% to 90% of their build – essentially beyond repair. An estimated 500+ residents had to be evacuated, many of whom lost most of their belongings in the blaze. Over 300 people were displaced into temporary shelters. The heat melted vehicles; nearly 400 cars and motorbikes were damaged or destroyed in the streets and driveways. Infrastructure was also impacted – power supply tripped in the area and a portion of a nearby highway was closed as a precaution until the site was secured. Cracks and soot marks extended hundreds of meters from the explosion center.

Image source: Bernama / New Straits Times, April 2, 2025.

Upon concluding the technical investigation, Malaysian authorities took immediate actions. It was emphasized that no negligence or third-party interference had caused the incident – the pipeline had been operated within its pressure limits and met all technical specifications prior to the failure. In light of that, the focus shifted to preventing a recurrence caused by geological factors. The Selangor state government announced the formation of a special committee under the Disaster Management Unit to study the incident and recommend changes. This committee includes experts from Petronas and government agencies, aiming to update policies on land-use planning around pipelines, improve approval processes for developments near pipeline rights-of-way, and incorporate climate change considerations (such as heavier rainfall patterns) into infrastructure risk assessments. A notable finding was that prolonged underground water retention and compromised drainage were contributing factors to the failure. Therefore, the committee is expected to propose stricter control of drainage and construction activities near pipelines to avoid water ingress and soil weakening.

Meanwhile, DOSH issued directives to Petronas Gas to identify all other pipeline segments at high risk of similar soil instability along its 2,680 km of gas pipelines nationwide. Petronas had reportedly already started this review, pinpointing areas with known soft ground or settlement issues, and was instructed to carry out immediate remedial works on those segments. For security reasons, the specific locations of concern were not publicly disclosed, but the directive indicated that a broad geotechnical audit was initiated. Remedial measures likely include underpinning or replacing soil under pipelines, adding supports or slabs, improving drainage, or even rerouting sections if necessary.

In summary, the Putra Heights explosion case study demonstrates a classic sequence of pipeline failure due to geotechnical causes: **soft saturated soil → settlement → pipeline strain and cyclic fatigue → crack → overload rupture → explosion**. It underscores how vital it is for pipeline operators to monitor ground conditions over the lifespan of a pipeline. What made this case particularly tragic was the location – passing through a residential zone – which amplified the consequences when failure occurred. The lessons from this incident are driving changes in Malaysia's pipeline safety management, particularly in integrating geological assessments into pipeline integrity programs. In the next section, we analyze the failure mechanisms highlighted by this case (and others like it) in more detail, and then explore advanced technologies that could help detect such problems earlier.

6.0 Case Study: United States (2018) – Revolution Pipeline Landslide Explosion

In September 2018, heavy rainfall in western Pennsylvania caused a landslide that ruptured the 24-inch Revolution natural gas pipeline shortly after it began operation. The sudden rupture released a massive volume of gas which ignited explosively, leveling a nearby house, toppling several high-voltage transmission towers, and scorching several acres of woodland. The pipeline (about 65 km long) was a newly built transmission line carrying Marcellus Shale gas and was in the process of being commissioned at the time of the incident. Fortunately, no injuries were reported (the residents of the house had evacuated), but the destruction underscored the devastating potential of geohazard-induced failures in steep terrain.

Image source: Pennsylvania PUC / NTSB investigation of Revolution Pipeline Explosion (Beaver County, USA), 2018.

Investigators determined that the pipeline route traversed an unstable slope where improper erosion control and backfill compaction during construction left it vulnerable to movement. Intense rainfall triggered ground subsidence and slippage on the steep hillside, causing the buried pipeline to bend and separate at a girth weld. The released gas found an ignition source, resulting in a girth-weld rupture and fireball. Regulatory authorities cited the operator (Energy Transfer) for inadequate geotechnical risk management. The company was fined and agreed to a settlement of about $2 million that included civil penalties and requirements for enhanced slope stabilization and monitoring measures. The pipeline remained shut down until the operator implemented corrective actions, such as improved drainage, hillside reinforcement, and revised start-up procedures, to prevent similar failures in the future. This case highlighted the need for rigorous geotechnical surveys and landslide mitigation in pipeline design and routing in Appalachian terrain.

7.0 Case Study: Peru (2004–2006) – Camisea Pipeline Landslide Failures

The Camisea pipeline system in Peru's Andes mountains suffered a series of ruptures and explosions in its early years due to unstable soil and slope failures along its route. The system consists of a 714 km, 32-inch gas pipeline and a parallel 540 km, 14-inch natural gas liquids (NGL) pipeline transporting gas from the Amazon jungle over the Andes to the coast. Within the first 30 months of operation, the NGL line ruptured six times, four of which were attributed to landslides or ground movement on steep slopes. Notably, on August 29, 2005, a section of the pipeline burst near Vinchos, releasing about 1,600 barrels of condensate, after the line was strained by unstable, shifting ground in the mountains. Another major failure on September 16, 2005 spilled ~7,000 barrels of liquids on a riverbank when earth pressures from a soil slip ("earthwork") crushed the pipe. The most catastrophic event occurred on March 4, 2006, near the jungle town of Echarati, where a landslide-related rupture on the NGL pipeline led to an explosion that injured three people (a woman and two children) and left a crater in the jungle. In total, over 14,000 barrels of hydrocarbon liquids were spilled in the first five ruptures, and one incident's gas leak ignited into an explosion and fire.

Geotechnical investigations concluded that intense rainfall and slope instability were the dominant causes of these failures. In several locations, deep-seated landslides and erosion had exposed or overstressed the buried pipelines, leading to loss of support and rupture. Post-incident reviews criticized the pipeline's design and construction, noting a failure to fully account for the region's landslide-prone geology. An independent assessment for the Inter-American Development Bank found evidence of shoddy construction practices (e.g. porous welds, possibly under-spec pipe) and identified sections of the route at high risk of geotechnical failure. In response, Peruvian authorities imposed nearly $1 million in fines on the operator (Transportadora de Gas del Perú consortium) for environmental damage and warned that the operating concession could be revoked after successive leaks. This prompted urgent remediation measures: the operator was required to reinforce slopes, improve drainage and erosion control, and enhance pipeline monitoring in critical geohazard zones. The Camisea case underlines the importance of thorough geological hazard assessment and robust engineering (route selection, trench design, pipe anchoring) when constructing pipelines across mountainous tropical terrain.

8.0 Case Study: China (2016) – Sichuan–East Gas Pipeline Landslide Explosion

A deadly geotechnical pipeline failure struck central China in July 2016 when days of torrential rain triggered a landslide that struck the Sichuan–East Gas Pipeline in Hubei province. The pipeline, operated by Sinopec, is a major 8 bcm/year transmission line carrying natural gas from Sichuan's gas fields across mountainous terrain to eastern China. In the incident, a rain-soaked hillside gave way and crushed the buried pipeline, causing a sudden rupture. The escaping high-pressure gas ignited in a massive fire that killed two people and forced emergency shutdown of that pipeline section. The blaze was visible from afar and disrupted gas supply, as Sinopec had to immediately cut off about 9.8 million cubic meters per day of gas flow through the line. The accident occurred in a remote area amid widespread flooding and slope failures; heavy monsoon rains had destabilized slopes along the pipeline right-of-way, demonstrating the vulnerability of infrastructure to extreme weather in the region.

Subsequent examination confirmed that the landslide was the proximate cause of the pipeline failure. Saturated soil and rock slid downhill, exerting excessive bending and shear forces on the buried steel pipe until it fractured. Sinopec and government regulators responded by halting gas through the pipeline and securing the site. Nearby gas wells feeding the line were shut in to prevent further fuel release. The company rerouted gas supply in coordination with PetroChina to maintain service to customers while repairs were undertaken. The damaged pipeline segment was excavated and replaced, and reinforcement works (such as slope grading and retaining structures) were carried out on the unstable hillside. This event prompted Chinese authorities to re-evaluate pipeline routes and emergency practices in geohazard-prone areas. Following a series of pipeline accidents, the government had already launched nationwide safety inspections and upgrades for oil and gas pipelines. The Sichuan–East pipeline explosion reinforced the need for stringent geotechnical risk management – from route selection and trench design to real-time slope monitoring – to prevent landslide-induced failures on critical energy infrastructure.

9.0 Discussion: Failure Mechanisms in Geotechnical Pipeline Failures

The Putra Heights case and similar incidents worldwide allow us to distill several key geotechnical and structural failure mechanisms that pipelines may undergo due to unstable soil conditions. Understanding these mechanisms is essential for engineers to design appropriate monitoring and mitigation strategies.

1. Ground Settlement and Loss of Support: Gradual soil settlement is a silent but dangerous process for pipelines. In Putra Heights, 24 cm of subsidence over decades might have gone largely unnoticed at the surface, but underground it meant the pipeline was slowly left hanging. When a buried pipeline loses continuous support from beneath, it behaves like a beam spanning a gap – inducing bending stress and high tensile strain on the top of the pipe and compressive strain at the bottom. The longer the span and the heavier the pipe (including its pressurized contents), the greater the stress. If the pipeline is rigidly constrained at both sides of the span, additional axial tension can develop as it sags. Over time, even small repeated deflections can cause low-cycle fatigue in the steel. The DOSH investigation explicitly noted that the Putra Heights pipeline underwent cyclic loading as it moved in the softened ground, leading to fatigue striations on the fracture surface. This scenario is emblematic of settlement-induced failures: they develop slowly, often without triggering an alarm in day-to-day operations (no immediate pressure loss or leak), until the accumulated damage reaches a critical point.

Mitigating settlement issues requires both geotechnical and structural solutions. Geotechnically, one should ensure proper compaction of backfill during construction and monitor areas of known subsidence (e.g., in peat soil, karst cavities, or where groundwater drawdown occurs). Structurally, pipelines in soft ground can be given extra margin – for instance, using thicker-walled pipe to increase stiffness, or installing continuous concrete support slabs or pilings at intervals to limit how far the pipe can sag if soil gives way. Importantly, cases like this highlight that pipeline integrity management programs must include periodic geodetic surveys (to detect if the pipeline elevation is changing) or in-line inspection tools that can measure bending strain along the pipe's length.

2. Soil Saturation and Weakening: Excess water in soil is a major cause of instability. In the Putra Heights area, the soil was found to be water-saturated and containing natural aquifers. When soils (especially clays and silts) become saturated, their shear strength diminishes – essentially, the soil particles lose frictional contact, and the soil can behave fluid-like under load. A pipeline buried in such mud is prone to differential settlement as pockets of soil wash out or consolidate. Additionally, water can erode fine particles, creating voids. Saturated conditions often occur from poor drainage: heavy rainfall or leakage from nearby water infrastructure can raise the water table. In tropical climates with monsoon seasons (as in Malaysia), intense rainfall events can rapidly change subsurface conditions. In hillside or slope areas, water saturation is the precursor to landslides; in flatter areas, it leads to long-term subsidence or even sudden collapse (sinkholes). The presence of a monsoon drain near the pipeline suggests that flood water periodically flowed through, and if that drain leaked or overflowed, it could have further saturated the soil around the pipeline.

A related issue is climate change – more erratic and intense rainfall can exacerbate soil saturation problems. Investigators of Putra Heights cited long-term underground water accumulation and compromised drainage as factors. In general, pipeline operators must manage water around their pipelines: ensuring drainage ditches, culverts, and trench breakers function to divert water away. They may also use buried French drains or vertical sand drains to relieve water pressure in soils. Another measure is selecting proper bedding material: laying pipelines on a stable foundation (e.g., crushed rock or engineered fill) can help reduce the risk that a little soil softening will cause an immediate loss of support.

3. Strain-Induced Cracking and Tensile Overload: The end result of ground-induced pipeline stress is often a through-wall crack that leads to leakage or rupture. Cracks can initiate in different ways. In many soil movement cases, if the pipe is forced to bend significantly, the outer fibers of the steel on the convex side experience high tensile strain. Modern steel pipelines can tolerate some deformation (often up to ~0.5–1% strain) but beyond that, the steel may start to yield and micro-cracks can form at stress concentrators (like welds, scratches, or corrosion pits). In Putra Heights, the critical crack appeared at a girth weld, likely because the weld and its heat-affected zone had slightly different material properties and minor weld flaws can concentrate stress. Fatigue could have grown the crack incrementally with each cyclic load until a large portion of the wall's cross-section was cracked. At that stage, the next load cycle or pressure surge causes a tensile overload failure, snapping the remaining ligament of steel. The investigation described this as the damage developing slowly until it "caused a ductile failure which released gas and sparked a fire," indicating the steel likely stretched (ductile tearing) right before rupture – a hallmark of overload beyond the material's ultimate strength.

Some other global incidents echo this pattern: for example, the Denbury CO_2 pipeline in Mississippi (2020) also failed at a girth weld due to soil movement-induced axial tension. In seismic zones, pipeline welds have similarly failed when the ground displaced along faults or landslides. Tensile fractures in pipelines tend to open up widely, releasing a large volume of contents rapidly (which increases the chance of ignition for flammable products). On the other hand, compressive forces from soil movement can cause buckling (wrinkles) or girth weld fractures in compression – these may initially just cause a deformation without full rupture, but they severely weaken the pipe and can later become a leak or rupture if pressure is cycled.

To guard against strain-induced cracking, pipeline design codes in hazard-prone areas sometimes employ strain-based design criteria, which involve using tougher, more ductile steel that can deform plastically without fracturing, and performing advanced structural analyses for predicted ground movement. Additionally, in-line inspection (ILI) tools that measure pipe geometry (geo-pigs or deformation pigs) can detect developing bends or out-of-roundness in the pipeline, providing early warning of excessive strain before a crack forms. Post-construction, welds can be assessed via ultrasound or magnetic methods to ensure quality, but it is the changing soil conditions that must be watched thereafter.

4. Compounding Factors – External Loads and Development: The environment around the pipeline also plays a role. In Putra Heights, urbanization around the pipeline right-of-way may have changed loading on the soil. New buildings or roads can impose extra weight and cause settlement. Heavy vehicles crossing above (if the cover is shallow) could stress a pipeline or compact the soil differently. *The Edge Malaysia* noted dense urban development and compromised monsoon drains as part of the problem. This suggests that unauthorized construction or insufficient buffer zones around the pipeline might have contributed to the soil instability. It raises an important point: pipelines often have an easement or right-of-way with restrictions, but enforcement can lapse over decades. Even tree roots can penetrate and destabilize soil or affect drainage infrastructure near pipelines.

Additionally, operational factors can compound strain: temperature changes in the pipeline (from gas temperature variations) cause it to expand/contract, which – if the pipe is constrained by soil – can induce cyclic axial stresses. However, in the cases discussed, the dominant factors were geotechnical in nature.

In summarizing the failure mechanisms, the Putra Heights incident essentially boiled down to a geotechnical failure leading to a structural failure. The ground could no longer hold up the pipeline, and as the pipe sagged and moved, it cracked and broke. This analysis highlights why multidisciplinary approaches (geotechnical + structural engineering) are needed for pipeline safety in unstable ground.

With these mechanisms understood, the logical next step is prevention and early detection. We have established that such failures usually give some warning signs: ground deformation, pipeline strain, perhaps small leaks or unusual stresses before the big break. In the following section, we explore the technologies and techniques available to detect these warning signs and to proactively manage pipeline integrity in the face of soil instability. In particular, we discuss how advanced sensing technologies like fiber optics and satellite monitoring can catch ground movement, how UAV-based methods (like LiDAR mapping or magnetic surveys) can quickly assess pipeline condition after events, and how integrating these into a pipeline's SCADA and digital twin models could enable predictive maintenance. Special focus is given to the Skipper NDT drone platform, as a novel technology for non-invasive pipeline strain assessment that could be integrated into monitoring programs.

10.0 Preventive Technologies for Early Detection of Pipeline Geohazards

Preventing pipeline failures due to soil instability hinges on early detection of problematic ground or pipe strain and timely intervention (such as reducing pressure or reinforcing support) before a failure occurs. Traditional mitigation includes route selection to avoid unstable areas and engineering solutions like deeper burial or protective casings. However, once a pipeline is in operation, continuous monitoring becomes the frontline defense. In recent years, a suite of advanced technologies has emerged to monitor both the pipeline and its surrounding environment. Below, we discuss these technologies and how they can be integrated for a comprehensive monitoring system. **Table 1** (at the end of this section) provides a comparative summary of the key technologies.

10.1 Distributed Fiber Optic Sensing (DSS)

Distributed fiber-optic sensing turns the pipeline itself into a monitored structure that "feels" the ground moving. Using the principle of fiber-as-a-sensor, a fiber optic cable installed alongside or attached to a pipeline can act as thousands of strain gauges and thermometers along the pipe's length. By sending laser pulses and measuring backscatter signals (e.g. via Brillouin or Rayleigh scattering), **distributed strain sensing (DSS)** can detect minute stretches or compressions in the fiber, effectively measuring strain at every meter of the pipeline. This means if a section of pipeline starts bending or stretching due to soil movement, the fiber will experience corresponding strain and an alarm can be raised. The technology can pinpoint the location of a strain event to within a few meters over many kilometers of pipeline. In addition to strain, distributed temperature sensing (DTS) in the same fiber can detect thermal anomalies (important for spotting leaks, as escaping gas cools the area or hot liquids warm it). There is also distributed acoustic sensing (DAS), which picks up vibrations – useful for detecting sudden ground movement, rockfalls, or even the sound of a pipeline cracking. An integrated fiber system, like the Omnisens **Lynx**, offers all three: strain, temperature, and vibration monitoring to cover landslides, subsidence, erosion, leaks, and intrusions.

The advantage of fiber optic DSS is continuous, real-time coverage along the entire pipeline. For instance, if a landslide begins to slowly push on a buried pipeline, the fiber will register increasing strain and send an alert when thresholds are exceeded. In tests, fiber sensors have detected ground displacements of just a few centimeters, providing an early warning well before catastrophic failure. Fiber systems can be linked into the pipeline's SCADA (Supervisory Control and Data Acquisition) system – as soon as an anomaly is detected, the SCADA can notify operators or even trigger automated actions. The main limitation of DSS is the need to install the fiber cable along the pipeline, which is easiest done during construction or by retrofitting (trenching alongside the pipeline to lay fiber). It can be costly to implement over long distances, but many new pipelines now include fiber optics as a standard practice for both communications and sensing. Given the Putra Heights scenario, a fiber system likely would have detected the incremental strain build-up as the pipe sagged, potentially allowing preemptive maintenance.

10.2 Satellite Interferometric Synthetic Aperture Radar (InSAR)

Satellite **InSAR** has revolutionized our ability to monitor ground deformation over large areas. By analyzing phase differences between radar images of the same area taken at different times, InSAR can measure how much the ground surface has moved – with accuracy on the order of millimeters. The beauty of InSAR is that it requires no instrumentation on the ground; satellites continually orbit and collect radar data. For pipeline monitoring, InSAR is exceptionally useful to identify broad-scale subsidence or slope movements along the pipeline route. It can, for example, reveal that a particular stretch of pipeline right-of-way is sinking year by year (perhaps due to soil consolidation or peat decay), or that a known landslide-prone hillside is inching downhill. Modern techniques like Persistent Scatterer InSAR can even monitor specific features (buildings, rocks, etc.) over time to detect subtle accelerations in ground movement. In pipeline applications, InSAR has been used to complement on-ground sensors: one case study demonstrated detection of slow-moving landslides above a pipeline that would be hard to catch with point sensors.

For the Putra Heights pipeline and others in urban areas, InSAR could be employed to monitor whether the pipeline corridor is experiencing settlement. Examination of historical satellite data over Putra Heights might have shown slight downward motion of the terrain in the years prior. Satellite monitoring is especially powerful for long linear assets – an entire 100 km pipeline can be scanned for movement hotspots, which can then be targeted for ground inspection. The limitation of satellite InSAR is the revisit rate (depending on the satellite, could be every few days to a couple of weeks) and the fact that dense vegetation or changes on the ground (like construction) can reduce data quality. Also, InSAR measures the ground surface; it infers pipeline movement indirectly (if the ground above moves, the pipeline likely does too). Despite these limitations, the wide coverage and high sensitivity of InSAR make it a cornerstone of pipeline geohazard monitoring. Operators today often use InSAR data layers in their GIS systems to flag where additional measures (like fiber sensors or site visits) might be needed.

10.3 Unmanned Aerial Vehicle (UAV) LiDAR Surveys

Drones equipped with LiDAR (Light Detection and Ranging) sensors can produce extremely high-resolution 3D models of the terrain along a pipeline. **UAV LiDAR** can penetrate through vegetation (by capturing multiple returns from laser pulses) to map the actual ground surface, even in jungles or forests. By flying a drone along the pipeline right-of-way, one can detect changes in topography such as new sinkholes, developing landslide scarps, or settlement troughs. For example, if a section of ground has settled a few centimeters since the last survey, a comparison of LiDAR-derived digital elevation models (DEMs) will show that depression. UAV LiDAR is incredibly precise – often achieving 5–10 cm or better accuracy in elevation. Moreover, drones can be deployed on-demand after extreme weather events. In the aftermath of heavy rains or an earthquake, a quick drone flight could identify if any part of a pipeline's route has shifted or if there's visible distress (cracks on the ground surface, etc.).

In addition to LiDAR, drones carrying high-resolution optical cameras (or even thermal cameras) are used for pipeline corridor patrol. They can spot issues like soil erosion around a pipeline right-of-way, water pooling (which signals poor drainage), or landslide movement (tilted trees, fresh soil disturbances). Some advanced setups use photogrammetry to also create 3D terrain models from overlapping images. The advantage of UAVs is agility and resolution: they can be flown low and slow for a detailed inspection that satellites or planes might miss. In infrastructure contexts, LiDAR drones have been shown to effectively monitor subsidence and deformation with very fine detail, and they are particularly helpful in areas that are remote or hard to access on foot.

The downsides include limited range (due to battery life) and the need for clear weather and airspace permission to fly. However, for targeted surveillance of known risk areas, drones are quite cost-effective. For instance, after noticing via InSAR or fiber data that a certain segment is behaving abnormally, a UAV survey can provide a closer look and quantify how the ground and pipeline alignment have changed. LiDAR data from drones can also feed into digital twin models (discussed later) for simulating pipeline strain under the mapped deformations.

10.4 Ground Penetrating Radar (GPR)

GPR is a geophysical method that uses high-frequency radio wave pulses to image the subsurface. While traditionally used to locate pipes and cables, GPR can also detect anomalies like voids, loose soil zones, or unusual moisture content below ground. For pipeline safety, GPR is particularly useful if we suspect underground erosion or void formation near a pipeline (for example, if a leak washed away soil or if water flow created cavities). By moving a GPR antenna over the ground (often mounted on a cart or vehicle), technicians can see reflections from different soil layers and identify disturbances. In a scenario like Putra Heights, if residents or maintenance crews notice sinkholes or minor ground depressions near the pipeline right-of-way, GPR can be employed to assess whether there are underground voids undermining the pipe. GPR typically penetrates up to ~5–10 m deep in soil (depth depends on soil conductivity and antenna frequency), which is sufficient for shallow pipelines.

The advantage of GPR is that it provides a direct subsurface image, which other methods (like visual inspection or even LiDAR) cannot. It could confirm, for instance, that the bottom of the pipe is not in contact with soil for a certain span (which would appear as an air gap reflector beneath the pipe). However, GPR surveys are localized in coverage and require skilled interpretation – they are best used when a particular area is under scrutiny, rather than for continuous monitoring. Still, as part of a toolkit, GPR is invaluable for diagnosing specific geotechnical issues (like detecting a hidden cavity caused by soil washout before it leads to a collapse). In terms of preventive maintenance, pipeline operators might use GPR around critical crossings or known karst areas periodically to ensure no dangerous voids are developing.

10.5 Drone Magnetometry (Skipper NDT)

A cutting-edge technology for pipeline strain monitoring is drone-based magnetometry. The **Skipper NDT** platform exemplifies a novel approach: it uses an unmanned aerial vehicle equipped with sensitive magnetometers to perform *Large Standoff Magnetometry (LSM)* –

essentially mapping the magnetic field of a buried pipeline from above ground. This works because pipelines, being steel, have a certain magnetic "signature" due to both the Earth's field and residual magnetization from the manufacturing process. When a steel pipeline is strained (bent or stretched), its magnetic properties change slightly. Skipper NDT's system capitalizes on this by collecting magnetic data over the pipeline route and using algorithms to infer the 3D position of the pipeline and any bending strain it may be experiencing. In effect, it can detect if a pipeline has moved from its original position or developed curvature that could indicate strain.

One of the major benefits of Skipper NDT is that it is non-contact and fast. According to the company, the drone can survey approximately 1.5 km of pipeline per day, capturing a continuous magnetic map. It's fully remote (the drone flies the pattern autonomously), enhancing safety by keeping operators out of potentially dangerous areas. The system is designed for use on pipelines of various diameters (from small distribution lines up to large transmission lines). A key deliverable of a Skipper NDT survey is a high-precision digital twin model of the pipeline – showing the exact centerline in XYZ coordinates and highlighting any sections where the pipeline's curvature deviates from normal (i.e., where bending strain is present). Essentially, if a section of pipeline has been deflected downward by 15 cm (like in Putra Heights), the Skipper system would detect that deviation in the pipeline's depth profile and flag the bending strain at that location.

Skipper NDT has already been used by major operators (e.g., PG&E, Chevron, Enbridge) and validated in industry research projects. It is particularly attractive for surveying areas that are hard to access on foot (like river crossings or steep terrains), or for rapid response after events like earthquakes or landslides to assess pipeline integrity. Integrating Skipper NDT into a monitoring program could work as follows: perform baseline drone magnetic surveys to capture the as-built pipeline profile, then conduct follow-up surveys annually or after any suspected geohazard incident. Changes can be detected by comparing the magnetic maps. Because it creates a digital twin of the pipeline, this data can feed directly into integrity assessment software – engineers can run stress analyses on the as-measured pipeline geometry to see if any observed bending is approaching critical strain levels.

By focusing on bending strain assessment, Skipper NDT fills a gap between external ground monitoring (like InSAR, LiDAR) and internal inspection (ILI tools). It effectively measures the pipeline's own deformation from the outside without needing to send a device inside the pipe or perform an excavation. In the Putra Heights scenario, a Skipper NDT survey might have identified the developing sag in the pipeline long before failure, indicating that the pipeline at that location had deviated from its expected alignment and experienced bending strain beyond acceptable limits. This could have prompted a maintenance action such as soil grouting under the pipe or installing additional supports.

10.6 SCADA Integration and Smart Monitoring

Modern pipeline operations use **SCADA** (Supervisory Control and Data Acquisition) systems to continuously monitor pressures, flow rates, temperatures, valve statuses, and other operational parameters. SCADA is also central to leak detection systems (tracking inlet/outlet balance or using computational pipeline monitoring for transients). For geohazard monitoring, the concept is to integrate all the aforementioned sensor inputs into the SCADA or a dedicated integrity management platform. For example, if fiber optic sensing is deployed, its alerts (strain alarms or unusual vibration detections) can be configured to annunciate in the control room.

SCADA can also monitor instruments like inclinometers or strain gauges if those are installed on the pipeline or in the ground (in some cases, critical slopes have been instrumented with tilt sensors or piezometers that feed data back). The benefit of SCADA integration is immediate situational awareness and potentially automated response. An operator seeing a high strain alarm could preemptively reduce the pipeline pressure as a precaution, mitigating the risk of rupture by lowering stress in the pipe.

Furthermore, SCADA data itself can sometimes indirectly indicate geotechnical issues. For instance, a slight drop in pressure or flow might indicate a small leak caused by a pipeline seam opening under stress. Or a spike in operating pressure might result from a pipe bore reduction due to a kink or buckle forming (though such signals are subtle). Typically, SCADA alone is not enough to catch soil instability, but in conjunction with dedicated sensors it becomes the nerve center for a "smart pipeline." The key is to ensure all relevant geohazard sensor outputs (fiber strain, tiltmeters, weather data, etc.) are integrated into the SCADA dashboard or alarm system, and that operators are trained to interpret and respond to them.

10.7 Digital Twin Modeling and Predictive Analytics

The concept of a **digital twin** is increasingly being applied to pipeline systems. A digital twin is a virtual replica of the physical pipeline that can simulate its behavior under various conditions in real time, synchronized with live data. By integrating geotechnical data (from surveys, InSAR, etc.), material data (pipe grade, toughness, weld properties), and inline inspection data (wall thickness, corrosion, etc.), a digital twin can be used to run scenarios and assess pipeline integrity continuously. In the context of geohazards, if we feed ground movement data or strain sensor data into the digital twin, the model can calculate the resulting stresses on the pipe. Conversely, if weather forecasts predict a major rainstorm, the twin could predict which slopes along the route are likely to move and which pipeline segments would be stressed by that movement. For example, Teren's pipeline geohazard platform integrates digital twins with advanced geohazard modeling to pinpoint where weather or seismic events could compromise the pipeline.

Digital twins are powerful for what-if analysis and risk prioritization. They can help answer questions like: "If this hill subsides by 10 cm, will my pipeline survive? If not, what is the critical displacement that would cause failure?" – thus identifying which areas need the most urgent monitoring or reinforcement. In the Putra Heights case, had such a digital model existed, it might have shown that even a few tens of centimeters of settlement would over-stress the pipeline, flagging it as a high-risk segment requiring frequent inspection or ground improvement.

An integrated technology approach is ideal: no single tool is a silver bullet. The best practice is to use multiple layers of defense. For instance, InSAR can continuously screen the entire pipeline length for any ground motion. Fiber optics (DSS) provide continuous feedback on the pipeline's own strain and can catch localized settlement or third-party digging. Skipper NDT or UAV LiDAR can be deployed periodically or after triggering events to get a detailed assessment of pipeline geometry and ground condition. All these data streams can be funneled into a control system or digital twin to analyze trends and predict failures. Importantly, the human factor remains vital – having trained pipeline integrity engineers and geotechnical experts interpret the data and make maintenance decisions is key. Technology provides the eyes and ears on the system; experts provide the judgment.

Table 1: Advanced Technologies for Early Detection and Monitoring of Underground Pipeline Threats

Technology	Monitored Parameters & Threats Detected	Advantages	Limitations
Distributed Strain Sensing (Fiber Optic DSS)	*Strain* along pipeline (bending, axial); also *temperature* and *vibration* with DTS/DVS. Detects ground movement stressing pipe, leaks (thermal changes), third-party intrusion (vibrations).	– Continuous **real-time** monitoring of entire pipeline length.– High sensitivity: detects minute strain changes and pinpoints location within meters.– Multi-functional: one fiber cable can sense strain, heat, and acoustics, covering various threat types.– Integrates with SCADA for instant alerts and automatic shutdown triggers.	– **High installation cost**, especially for retrofitting existing lines (requires burying cable along pipeline).– Data processing and interpretation require expertise (large data volumes).– Fiber can be damaged by dig-ups or lightning, so needs protection and maintenance.
Satellite InSAR	*Ground surface displacement* (vertical and horizontal) over broad areas. Detects land subsidence, slow-moving landslides, and uplift along pipeline corridors.	– **Wide area coverage**: monitors hundreds of km², entire pipeline routes without ground instruments.– Very high **accuracy** (mm to cm scale ground motion detection) for early warning of gradual soil movements.– **All-weather, night or day** capability (radar penetrates clouds and works at night).– Retrospective analysis: historical satellite data can be analyzed to see past ground stability trends.	– **Intermittent data**: depends on satellite passes (daily to bi-weekly). Rapid changes may be missed between acquisitions.– Reduced effectiveness in areas with heavy vegetation or snow (loss of coherent radar targets).– Primarily detects surface movement; may not directly see subsurface voids or very localized sinkholes under a pipeline.– Requires expert processing; commercial InSAR services add cost.
UAV LiDAR Surveys	*High-resolution terrain mapping* (Digital Elevation Models) and *surface change detection*. Detects subtle ground deformation, slopes, erosion, and overland	– **High resolution 3D data** (point clouds) reveals small ground shifts, cracks, or depressions that indicate instability.– **Penetrates vegetation** to get true ground surface model (useful in jungles or forests).–	– **Line-of-sight needed**: affected by extreme weather (cannot fly in heavy rain or high winds).– Limited flight time (battery constraints) – may require many flights for long pipelines.– Data processing for LiDAR is

	pipeline route changes.	Flexible deployment: drones can be flown on-demand after heavy rains, earthquakes, or regularly for trend analysis.– Also captures imagery – visual inspection of right-of-way for signs of distress (e.g., leaning poles, ground fissures).	compute-intensive; comparing point clouds over time needs specialized software.– Regulatory constraints on UAV flights (airspace permissions) can affect deployment.
Ground Penetrating Radar (GPR)	*Subsurface imaging* of shallow soil layers (up to ~10 m). Detects voids, sinkholes, eroded zones, and pipeline location/depth.	– **Direct void detection**: can confirm if empty spaces or soil washouts exist around a pipeline (which could lead to loss of support).– Useful for targeted investigations where suspected problem (e.g., after a small cave-in near a pipeline, to see if more voiding is present).– Non-invasive and quick to deploy in the field over a small area; immediate results can be seen in radargrams by trained operators.	– **Localized coverage**: not practical for continuous monitoring over long distances, used in spot-checks or surveys of limited length.– Performance depends on soil type: clay or wet soils attenuate radar signals, limiting depth and clarity..– Requires interpretation by experts; false positives/negatives possible for untrained eye (e.g., distinguishing a tree root from a void).– Depth penetration and resolution trade-off (higher frequency antennas give better resolution but shallower depth).
Drone Magnetometry (Skipper NDT)	*Pipeline magnetic field mapping* and derived *pipeline 3D position/strain*. Detects pipeline movement, bending strain, or deformation by changes in magnetic signature.	– **Non-contact pipeline strain assessment**: finds bending or misalignment of pipe without excavation or inline tools.– Creates a **high-precision digital twin** of the buried pipeline route, even in areas difficult to access on foot.– **Fast deployment** by drone, covering ~1.5 km per day with automated flight.– Proven on multiple pipeline systems; can detect	– Currently a periodic survey tool (not continuous monitoring); needs scheduling of drone flights.– **Magnetic noise** considerations: urban environments or nearby power lines may interfere – requires filtering and processing.– Expertise needed to interpret magnetic data into strain values; proprietary algorithms are used, so operators rely on vendor analyses.– May not detect very small

		developing strain before it becomes critical (early repair planning).	strains below threshold; complementary to other methods (works best for clear geometry changes).
SCADA Integration & Analytics	*Operational parameters* (pressure, flow, temperature) and *sensor integration*. Indirectly detects leaks, ruptures (pressure drop), or unusual strain via sensor triggers.	– **Centralized monitoring**: single interface (SCADA) for operators to see both operational data and alarms from geohazard sensors (fiber, tilt meters, etc.) in real time.– Can trigger **automatic responses** (e.g., shut valves, ramp down pressure) if a critical alarm from a sensor is received, potentially preventing a rupture from propagating or a leak from igniting.– Historical data logging for trend analysis and post-event forensic analysis (e.g., was there a pressure fluctuation correlating with ground movement time?).	– SCADA by itself does not measure ground movement; it's only as good as the external sensors integrated into it.– **False alarms** need to be managed to avoid unnecessary shutdowns (requires well-calibrated thresholds and sensor validation).– Ensuring **cybersecurity** and reliability of data from numerous field sensors is an added challenge as systems become more interconnected.
Digital Twin Modeling	*Virtual simulation of pipeline* using live data feeds (sensors, environmental data, ILI results). Predicts stresses and hotspot risks under various scenarios.	– **Predictive capability**: simulate impacts of potential ground movement before they happen – e.g., "if 5 cm of settlement occurs at X, what is the stress in the pipe?" allowing proactive mitigation.– Integrates multidisciplinary data: material properties, corrosion data, geohazard maps, weather forecasts – giving a holistic view of integrity. – Helps in **risk prioritization**: digital twin can rank pipeline segments by	– Building an accurate digital twin is data-intensive and computationally complex; requires quality data from all sources (GIS, ILI, sensors, etc.).– **Model uncertainty**: if inputs are off or phenomena not understood, predictions may be inaccurate; needs continuous validation against real world observations.– High initial setup cost and need for specialized software and expertise to maintain the model.– Operators may face a learning curve to trust and effectively

		vulnerability, guiding where to focus monitoring and maintenance resources.– Supports training and scenario planning (operators can rehearse response to certain simulated failures).	use the digital twin outputs for decision-making.

11.0 Recommendations

Preventing pipeline failures due to soil instability requires a proactive, multi-layered strategy. Based on insights from the Putra Heights case study and the capabilities of current technologies, we propose the following key recommendations for pipeline operators and relevant authorities:

1. **Implement Integrated Geotechnical Monitoring Programs:** Operators should treat geotechnical threats with the same seriousness as corrosion or third-party damage. This means establishing a dedicated geohazard monitoring program that combines remote sensing, in-situ sensing, and regular field inspections. For instance, use satellite InSAR data routinely to screen for any subsidence or slope movement along the pipeline route. Integrate this with on-ground instruments in known high-risk areas (e.g., inclinometers on unstable slopes, or settlement markers in soft ground areas). Consider deploying distributed fiber optic strain sensors on critical pipeline sections (such as those passing through settlements or landslide-prone terrain) to get real-time strain feedback. All these data sources should feed into a common monitoring center, enabling data correlation (for example, if InSAR shows a hillside creeping and fiber strain is rising at the same location, that's a red alert). This integrated approach ensures no single point of failure – even if one method misses an issue, another will catch it.
2. **Prioritize High-Risk Pipeline Segments for Upgrades:** Use a risk-based framework to identify pipeline segments most vulnerable to soil instability – taking into account soil type, slope angle, historical land movements, drainage conditions, and potential consequences (e.g., proximity to population centers). Those segments should be prioritized for preventive action. Upgrades may include ground improvement (stabilizing soil via compaction grouting, installing retaining structures or deep piles to support the pipeline), or strain relief measures on the pipeline (such as adding expansion loops or using heavier wall pipe). In some cases, where feasible, rerouting a pipeline around a very hazardous zone might be justified if the hazard cannot be effectively mitigated. The Putra Heights incident underscores that pipelines in densely populated areas built on marginal soil require extra attention. The formation of the special task force in Selangor is a good model – other regions should similarly review pipeline routes in light of changing climate and land use, and enforce buffer zones where no heavy construction should occur above pipelines.
3. **Leverage Advanced Technologies (e.g., Skipper NDT) for Periodic Assessments:** Incorporate periodic high-tech surveys into the maintenance schedule. For example,

perform Skipper NDT drone surveys every few years, or after significant events, on key pipeline stretches to detect any emerging bending strain. The cost of such surveys is relatively low compared to extensive excavations or frequent inline inspections, and they can cover areas that internal inspection tools might miss (ILI "pigs" see internal anomalies but not global bending shape). Likewise, schedule UAV LiDAR overflights for steep or remote segments after heavy rain seasons or earthquakes to check for ground movement. These technologies act as an "eye in the sky" to catch issues that ground patrols might miss. It is advisable to establish contracts or partnerships with specialized service providers (for InSAR, LiDAR, magnetometry, etc.) so that data can be collected and analyzed swiftly when needed. Running tabletop exercises with these technology providers can ensure that in an emergency (such as a reported landslide), the team can deploy a drone or analyze satellite data within hours to advise on pipeline safety.

4. **Enhance SCADA and Leak Detection with Geohazard Inputs:** Upgrade pipeline SCADA systems to integrate geotechnical sensor alarms and even weather data. For instance, if an extreme rainfall event is forecasted for a region with known unstable slopes, SCADA could automatically raise the sensitivity of leak detection algorithms (since saturated ground might lead to landslides and pipeline strain). Consider implementing automated shutdown or pressure reduction protocols tied to sensor triggers in high-consequence areas. For example, if distributed fiber strain exceeds a critical threshold or a slope inclinometer registers rapid movement, the SCADA can issue an alarm and initiate a controlled shutdown or pressure reduction on that pipeline segment. Such automation must be carefully calibrated to avoid false trips, but given the potential consequences (as seen at Putra Heights), it may be prudent to err on the side of safety. Additionally, regularly train control room operators to recognize geohazard-related alerts – not just the usual leak or pressure alarms – and to respond according to predefined action plans.
5. **Develop Digital Twin Models for Predictive Maintenance:** Invest in building a digital twin of critical pipeline systems that includes geotechnical interaction modeling. Use it to run simulations of various scenarios – e.g., "What if the ground subsides 10 cm at this river crossing? Will the stress in the pipe exceed allowable limits?" – to identify current factors of safety and whether mitigation is needed proactively. The digital twin should be continuously updated with data from inspections (to update wall thickness or corrosion status) and from ground surveys (to update current ground profiles). By doing so, operators can move towards predictive maintenance, addressing an issue before it manifests as an incident. For example, the twin might predict that in five years, if current subsidence trends continue, a certain pipeline weld will be overstressed. This allows scheduling a strengthening or re-burial project well in advance. Regulators and companies should collaborate to include digital twin analysis in integrity management plans, especially for pipelines traversing difficult geology.
6. **Strengthen Regulatory and Planning Frameworks:** Authorities should update regulations to require explicit geohazard management in pipeline safety cases. This could include mandating geotechnical risk assessments for new pipelines (e.g., route studies to avoid unstable ground), as well as requiring existing pipelines to be periodically evaluated for soil movement impacts – similar to how they must be regularly inspected for corrosion under integrity management programs. In urban planning, better coordination is needed: no heavy structures or alterations of drainage should be permitted in pipeline rights-of-way without engineering review. In Selangor's response to Putra Heights, we see recommendations for legal reforms and development policy updates that consider climate risks in pipeline corridors. Local

governments and pipeline operators should share data; for example, operators could provide maps of high-risk zones along their pipelines so city planners know where landslides or subsidence could occur and impact communities.

7. **Improve Community Awareness and Emergency Preparedness:** Even with the best prevention, accidents may still happen. Pipeline operators should engage communities along the pipeline route in awareness programs about recognizing and reporting signs of ground movement or pipeline distress (for instance, if residents notice cracks in the ground, or smell gas, they should know whom to call and understand that it might be pipeline-related). Companies should also work with emergency responders to plan for geohazard-induced pipeline emergencies. In Putra Heights, quick actions like closing valves and evacuating residents were crucial. Regular drills for scenarios such as "pipeline rupture due to landslide" can help fire services, police, and medical teams coordinate effectively. It is also recommended to install automatic shut-off valves on pipeline segments in geohazard-prone areas to minimize the volume of release if a rupture occurs – the faster a broken line is isolated, the smaller the fire or spill will be. Overall, enhancing community preparedness and emergency response will reduce impacts when incidents do occur.

Implementing these recommendations requires investment and cross-disciplinary effort, but the cost is justified by the potentially catastrophic consequences of failures. The Putra Heights disaster, which caused massive property damage and human suffering, is a stark reminder that "natural" factors can be just as threatening as corrosion or human error. By leveraging 21st-century technology – from satellites in orbit to smart fibers underground – we can greatly improve early warning for pipelines under duress from Mother Nature. A combination of vigilant monitoring, engineering reinforcement, and informed operational control can nearly eliminate surprises. As climate change increases the frequency of extreme weather events (floods, heavy rain, permafrost thaw, etc.), such measures will only become more vital for the safe and sustainable operation of pipeline infrastructure worldwide.

12.0 References

The Star (2025). "Report: Soil instability, not foul play, led to pipe failure." [Wani Muthiah, *Nation* news, July 1, 2025]. – Investigation findings by DOSH on the Putra Heights pipeline explosion, attributing the cause to gradual ground instability (soft, moist soil causing lack of support). Describes cyclic loading, fatigue striations, and tensile overload in the pipeline, and rules out foul play.

The Star (2025). *Putra Heights pipeline blast – additional details.* – Continuation of The Star report, quoting Selangor MB Amirudin Shari: 24.3 cm soil settlement over 25 years, 15.9 cm pipeline shift, water-saturated soil with underground water reservoirs leading to soft ground and compromised drainage. Describes explosion impact: ~150 injured, flames up to 30 m, heat ~1000 °C, 8 hours to extinguish, 9.8 m deep crater.

Bernama (2025). "Putra Heights Gas Explosion: DOSH Confirms Pipe Met Technical Specs." – Official news agency report (June 30, 2025) on the DOSH press conference. Confirms pipeline met specs, but the lower part was not supported by soft, damp soil. Repeated cyclic loading caused stress lines and fatigue. Metallographic analysis showed tensile overload as the main cause of failure, developing slowly to a ductile failure and explosion. Mentions the investigation methodology (on-site, lab tests, simulations) and findings: fracture at a welded joint due to tensile stress, soft loose soil beneath, significant cyclic loading prior to failure. No sabotage; DOSH directed Petronas to review other high-risk pipeline segments.

The Edge Malaysia (2025). "Putra Heights blaze: Weak soil beneath gas pipeline the root cause, no criminal element found." [July 2, 2025]. – Emphasizes unstable soil as the cause of the April 1 explosion. Notes 1,254 people affected, 87 houses destroyed, 148 needing repairs. DOSH's statement: pipeline met specs but was not fully supported by soft, moist ground, leading to failure and fire. Metallurgical evidence of tensile overload and fatigue damage over time. Selangor MB's statement: 24.3 cm land subsidence over 25 years, pipeline displaced 15.9 cm. Environmental factors – unstable soil, prolonged underground water retention, compromised drainage/culverts, climate-related stress, and dense urban development – contributed to the failure. Announces a special task force to recommend legal reforms, review planning procedures, and update development policies accounting for climate risks in pipeline right-of-ways.

Pipeline Fighters Hub (2023). Article on PHMSA Consent Agreement over Denbury CO_2 pipeline rupture in Satartia, MS. – Quotes PHMSA Failure Investigation Report for the Feb 2020 rupture: "failure of the pipeline was a result of soil movement which caused excessive axial loading leading to failure at the girth weld. Area topography, soil type, and large amounts of rain… saturated and vertically eroded the loess soil on the side of the hill above the pipeline." Explains how wet soil slumped and snapped the pipe. Notes PHMSA's 2019 advisory bulletin on geohazards and that Denbury had 2–3 land movement issues per year on that route, indicating a known geotechnical risk. Highlights that an inadequate geohazard detection program was cited as a violation in the case. Illustrates a real-world example of heavy rainfall plus unstable soil causing a pipeline girth weld failure.

OFS Optics (2025). *Distributed Strain Sensing (DSS) – Fiber Optic Sensing for pipelines.* – Describes how optical fibers can serve as fully distributed sensors for strain using Stimulated Brillouin backscatter. "Using the fiber-as-a-sensor approach… installing specialized fiber optic cables along pipelines to gather strain events over great lengths in real-time. … DSS cables detect strain variation events associated with lengthy structures like pipelines… using time-of-flight analysis, these events are quickly pinpointed to help operators intervene before catastrophic events occur." Notes that BOTDR (Brillouin Optical Time Domain Reflectometry) equipment can interrogate the fiber and locate strain changes. Emphasizes real-time monitoring and precise localization of strain anomalies.

Down & Leighton (2020). *Pipeline Geohazard Detection Using Satellite InSAR.* – Explains why InSAR is suited for pipeline monitoring: "Satellite Interferometric Synthetic Aperture Radar (InSAR) is a monitoring system using radar images to measure displacement of the ground and structures… InSAR can cover wide areas and requires no specialized equipment on the ground. InSAR can complement other monitoring methods or even function as the sole monitoring method for more remote areas. In addition to identifying and measuring displacement associated with slow-moving landslides or subsidence, the amplitude/coherence information can also be used to detect hazards and other changes along a pipeline network." Notes advances enabling earlier detection of ground displacement and faster data updates. Highlights InSAR's wide coverage and high accuracy for ground motion, and its growing use in pipeline geohazard management.

US EPA CLU-IN. “Ground Penetrating Radar (GPR) – Geophysical Methods.” – Defines GPR: “a shallow, high-resolution geophysical method that uses high-frequency, pulsed electromagnetic waves to image the subsurface. A GPR unit transmits EM energy into the ground which is reflected, refracted, or scattered back to the surface depending on features it encounters (such as changes in geologic media or buried objects). Typically GPR is limited to depths ~10 m… High-frequency antennas (200–400 MHz) can achieve resolutions of a few cm at shallow depths… Typical uses: map subsurface features like depth to water table, soil strata, location of cavities and fractures in bedrock. Other applications include locating objects such as pipes, drums, tanks, cables, buried utilities; mapping landfill and trench boundaries….” This confirms GPR’s ability to detect subsurface voids and utilities to within a few centimeters resolution near the surface, making it useful for void detection around pipelines.

NumberAnalytics (2025). “Advanced Subsidence Monitoring Techniques” (Sarah Lee). – Discusses LiDAR’s role in subsidence monitoring: “Light Detection and Ranging (LiDAR) uses laser pulses to create high-resolution 3D models of the ground surface… LiDAR can be used for: creating high-resolution DEMs to monitor ground deformation; detecting subtle changes in topography, such as subsidence or landslides; analyzing spatial distribution of subsidence relative to geological structures.” Also mentions integrating LiDAR with other emerging technologies like drones for subsidence monitoring. Highlights LiDAR’s high accuracy and detail for topographic change detection, directly applicable to monitoring pipeline routes for ground shifts.

Omnisens (n.d.). *Omnisens Lynx – Geohazard prevention with fiber optics.* – Describes fiber optic strain and temperature monitoring for pipelines: “Detection and monitoring of the development of landslides, creep, subsidence and erosion is achieved using combined strain and temperature measurements… When the earth around the pipeline moves, the fiber optic sensing cable is strained, resulting in an alert. By including a fiber optic strain sensor, ground displacement of a few centimeters is detected and located to within a few meters anywhere along the pipeline.” Notes that alerts are displayed on a GIS system and communicated to SCADA, confirming that distributed fiber systems can catch small ground movements and integrate with pipeline SCADA for alarms.

Teren (2024). “Enhancing Pipeline Safety: Integrating Digital Twins and Geohazard Modeling.” – Summarizes the benefits of combining digital twins with geohazard models: “Geohazard modeling, when merged with the pipeline’s digital twin, allows simulation of various scenarios and assessment of their impact on pipeline integrity… Integration of pipeline material data, inline inspection data, and advanced geohazard modeling leads to dynamic, real-time views of pipeline integrity, enabling operators to prioritize assets at highest risk.” Also describes case studies where digital twin + ILI + geodata identified pipeline strain from ground movement that was later confirmed in the field, demonstrating practical value.

Zhang et al. (2024). “Interaction of pipelines with landslides: analysis of mechanical properties…” (*Vibroengineering Procedia*). – Provides examples of landslide-induced pipeline failures in China: “…In December 2015, a catastrophic landslide from a dam collapse in Shenzhen caused pipeline ruptures due to the immense impact force. This led to massive natural gas leaks, significant casualties, and disruption in gas supply to Hong Kong. Similarly, in July 2016, continuous heavy rain in Enshi, Hubei triggered a landslide that ruptured the West–East Gas Pipeline, causing gas leaks and explosions. Furthermore, the China-Myanmar gas pipeline in Guizhou experienced two rupture incidents due to landslides in 2017 and 2018, resulting in

substantial economic losses." These global cases reinforce how landslides (often rain-induced) have directly caused pipeline ruptures and major consequences.

North Dakota Monitor (2024). "Summit avoids landslides in ND pipeline route changes." – Reports that "a landslide contributed to an oil pipeline spill in North Dakota in 2016 and shifting soil caused a carbon pipeline rupture in Mississippi in 2020… The ND pipeline spill (Billings County) caused crude oil to contaminate Ash Coulee Creek… PHMSA confirmed a landslide caused the leak. In Satartia, MS, PHMSA blamed heavy rain and a landslide for the rupture of a CO_2 pipeline." Confirms the geotechnical causes of those incidents and that such knowledge is influencing route planning (Summit Carbon Solutions rerouted a CO_2 pipeline to avoid landslide areas). Underscores recognition by regulators and companies that soil instability is a tangible pipeline risk.

SAYS (2025). "Putra Heights Pipeline Fire: Photos of the Devastation." – A news feature with eyewitness details: flames soared "hundreds of metres into the air, forming a mushroom-shaped fireball." Visible from ~25 km away (in Kuala Lumpur). Reports displacement of 538 residents and 145 injured by April 2. Notes 237 houses affected, with 88 units (78 homes + 10 shops) up to 90% damaged, and 399 vehicles damaged. Provides context on the scale of destruction and human impact in Putra Heights, validating data on houses and injuries.

Malay Mail (2025). "After destruction and chaos, what comes next?" (April 2, 2025). – Describes the response and damage: fire started ~8:10 am, flames up to 500 m, visible from kilometers away. Nearly 200 homes severely damaged, ~305 residents displaced, over 100 treated in hospitals (no fatalities). Fire fully extinguished by 3:45 pm by 325 personnel from 11 agencies. Confirms 237 houses affected, 88 burned 10–90%, and 399 vehicles burned or damaged (225 completely burned, 174 partially). Summarizes that the Prime Minister and officials visited the site and that compensation would be provided. Reinforces the extent of damage and timeline, consistent with other sources.