JPAIR Multidisciplinary Research Volume 65 • July 2026
DOI: https://doi.org/10.7719/jpair.v65i1.1011

# Innovating Transmission Line Foundations in Mountainous Terrain: A Narrative Literature Review

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Originality: 100% • Grammarly: 95% • Plagiarism: 0%

## ABSTRACT

***Article History***

Received: 26 Oct 2025
Revised: 24 May 2026
Accepted: 10 Jun 2026
Published: 30 Jul 2026

***Keywords***— Anchor foundations Civil engineering, Geotechnical assessment, Mechanized construction, Mountainous terrain, Narrative literature review, Transmission line foundations

Transmission line projects in mountainous regions encounter persistent engineering challenges due to steep slopes, unstable soils, and logistical constraints. Foundation design, as a critical determinant of reliability and cost efficiency, requires integrated strategies that combine geotechnical rigor, construction management, and resource planning. This study employs a narrative literature review to synthesize research on five interconnected dimensions of foundation performance: terrain characteristics, foundation type selection, geotechnical assessment quality, construction methods, and budget allocation. Results highlight that slope gradient and soil type strongly influence bearing capacity and failure rates; anchor foundations provide time efficiency in accessible sites, while pad and pile foundations remain essential in weak soils. High-quality geotechnical assessments, supported by effective communication between design and field teams, reduce unexpected failures. Mechanized construction methods improve cost efficiency in moderate terrains but lose advantage in rugged zones where mobilization and equipment reliability are compromised. Budget allocation enhances outcomes only when mediated by efficient material logistics. The review concludes that sustainable transmission line foundation design in mountainous terrain requires an integrated approach that links technical rigor, financial planning, and logistics efficiency. This has practical implications for infrastructure planning in the Philippines, where terrain-sensitive strategies can reduce delays and costs. Future research should develop predictive models that combine terrain parameters with supply chain simulations to guide proactive design and investment decisions in the Philippine and Asian context.

## INTRODUCTION

Foundations are the backbone of civil engineering structures, particularly transmission line towers, bridges, and energy infrastructure. Their design and construction directly influence project timelines, costs, and long-term reliability. Failures at this stage can lead to catastrophic consequences, including structural collapse, service interruptions, and massive financial losses.

The Philippine context, with its mountainous terrain and frequent exposure to rainfall and seismic activity, presents unique challenges for transmission line projects. Terrain-sensitive risks such as slope gradient, soil instability, and logistical constraints complicate foundation design and installation. Scholars and practitioners have therefore devoted significant attention to understanding the multiple variables that influence foundation performance, ranging from terrain characteristics and soil conditions to construction methods, geotechnical assessments, and budget allocation. However, few empirical studies in the Philippine context directly examine transmission line foundations in mountainous terrain. This gap highlights the need for integrated approaches tailored to local conditions. The research problem addressed in this paper is how terrain, geotechnical assessment, construction methods, and budget allocation interact to influence foundation reliability in Philippine mountainous regions.

The literature emphasizes that terrain characteristics—particularly slope gradient and soil type—are decisive factors in determining structural reliability.

Steeper slopes increase lateral earth pressures and reduce bearing capacity, while unstable soils such as expansive clays or loose sands heighten risks of settlement, erosion, and collapse (Alkahtani, 2025; Hu et al., 2026; Rotaru et al., 2022). Closely related to terrain is the choice of foundation type. Anchor, pad, and pile foundations each offer distinct advantages and limitations depending on site conditions. Anchor foundations are often associated with shorter construction times due to their rapid installation and immediate load capacity, particularly in accessible sites (Chandra Sekhar & Duggal, 2019; Acidri, 2019). Pad and pile foundations, while structurally robust, require extensive excavation, reinforcement, and curing, making them more time-intensive (Das & Sobhan, 2013).

Another critical determinant of foundation performance is the quality of geotechnical assessments. Numerous forensic studies of foundation failures attribute problems not to design flaws but to inadequate site characterization. Peck (1969) and Fellenius (2017) emphasized that insufficient exploration scope is a primary cause of unexpected failures. Hussaina et al. (2022) confirmed that accurate geotechnical parameter assessment is essential for predicting bearing capacity, while Aruna & Arulselvan (2017) identified inadequate investigation as a recurring cause of distress. Importantly, the literature also stresses the role of communication between design and field teams in mediating the benefits of geotechnical assessments. SAALG (2025) and Saalg (2025) noted that miscommunication often leads to misaligned assumptions, while effective collaboration ensures that geotechnical insights are translated into practical construction strategies.

The construction method itself is another major variable influencing cost efficiency and performance. Mechanized methods—using cranes, drilling rigs, and automated equipment—have transformed foundation installation by reducing labor costs, accelerating schedules, and improving precision (Liu & Tian, 2024). Alsanabani et al. (2023) showed that mechanized approaches aligned with value engineering principles optimize both cost and sustainability. However, the literature consistently notes that mechanization's benefits are terrain-dependent. In moderate terrains, mechanization thrives due to ease of mobilization and high utilization rates. In highly rugged zones, logistical challenges, equipment breakdowns, and weather disruptions erode its cost advantage (Hu et al., 2026; Shahbazi et al., 2019).

Finally, the literature underscores the importance of budget allocation as a foundational determinant of project success. Adequate funding enables comprehensive geotechnical investigations, high-quality materials, and advanced construction technologies. Mehta and Monteiro (2014) highlighted that investment in high-performance concrete improves durability, while Kulhawy and Mayne (1990) argued that conservative design requires sufficient budgetary support. However, the translation of budget into performance outcomes is mediated by material logistics, particularly in mountainous terrain. Prakash et al. (2024) emphasized that supply chain efficiency is critical in such environments, while Hu et al. (2026) showed that poor logistics erode the benefits of higher budgets. Golder Associates (2016) confirmed that pipeline foundations in rugged terrain required both adequate funding and efficient logistics to achieve cost efficiency.

Taken together, these five hypotheses—terrain characteristics, foundation type, geotechnical assessment, construction method, and budget allocation—represent interconnected dimensions of foundation performance in challenging terrains. The literature consistently demonstrates that no single factor operates in isolation. Terrain influences foundation type selection; geotechnical assessments inform construction methods; budget allocation determines the feasibility of advanced technologies; and logistics efficiency mediates the translation of financial investment into tangible outcomes. This holistic perspective underscores the need for integrated approaches that combine technical rigor, financial planning, and logistical coordination.

## Theoretical Foundations of Transmission Line Foundation Performance

The study of transmission line foundations in mountainous terrain requires a robust theoretical framework that integrates geotechnical engineering principles, construction management strategies, and infrastructure economics. The five hypotheses examined in this review—terrain characteristics, foundation type, geotechnical assessment, construction method, and budget allocation—represent interconnected dimensions of foundation performance. Each hypothesis is anchored in established theory but contextualized by the unique challenges of mountainous environments.

## The Influence of Slope Gradient and Soil Type on Transmission Line Foundation Performance

This discussion is grounded in soil mechanics and slope stability theory, pioneered by Terzaghi (1943) and expanded by Skempton and Bjerrum (1975). Terrain slope and soil type directly influence bearing capacity, lateral earth pressures, and settlement behavior. Steeper slopes reduce the factor of safety, while unstable soils such as expansive clays, loose sands, and collapsible loess introduce risks of heave, liquefaction, and erosion. Contemporary studies (Alkahtani, 2025; Hu et al., 2026; Rotaru et al., 2022) confirm that slope gradient and soil type are decisive determinants of transmission tower reliability. This principle rests on the understanding that environmental constraints are fundamental determinants of engineering performance.

**Anchor Foundations and Construction Time Efficiency Compared to Pad and Pile Foundations**

This discussion draws on structural engineering and construction management theory, which emphasizes the trade-offs between shallow and deep foundation systems. Anchor foundations, designed to resist uplift and lateral forces, provide rapid installation and immediate load capacity (Hannigan et al., 2006: Littlejohn & Bruce, 1975). Pad foundations distribute loads over a wide area but require extensive excavation and curing (Das & Sobhan, 2013). Pile foundations transfer loads to deeper strata, offering robustness in weak soils but demanding specialized equipment and longer installation cycles (Reese et al., 2025).

Comparative studies confirm that foundation type selection must balance engineering needs with logistical realities. This principle is anchored in the understanding that structural efficiency is terrain-dependent and accessibility-mediated (Acidri, 2019; Chandra Sekhar & Duggal, 2019).

**The Role of Assessment Quality and Communication in Reducing Foundation Failure Rates**

This discussion is rooted in geotechnical investigation theory and risk management frameworks. Peck (1969) and Fellenius (2017) emphasized that inadequate site characterization is a primary cause of unexpected failures. Hussaina et al. (2022) confirmed that accurate parameter assessment is essential for predicting bearing capacity, while Aruna and Arulselvan (2017) identified inadequate investigation as a recurring cause of distress.

Importantly, communication between design and field teams mediates the benefits of geotechnical assessments. SAALG (2025) noted that miscommunication often leads to misaligned assumptions, while effective collaboration ensures that geotechnical insights are translated into practical construction strategies. The principle guiding this discussion is that knowledge quality and communication are critical mediators of engineering reliability.

**Mechanized Construction Methods and Cost Efficiency in Foundation Installation**

This discussion is informed by construction technology and value engineering theory. Mechanized methods—using cranes, drilling rigs, and automated equipment—reduce labor costs, accelerate schedules, and improve precision (Alsanabani et al., 2023; Liu & Tian, 2024). However, terrain complexity moderates mechanization's benefits. In moderate terrains, mechanization thrives due to ease of mobilization and high utilization rates. In rugged zones, logistical challenges, equipment breakdowns, and weather disruptions erode its cost advantage (Hu et al., 2026; Shahbazi et al., 2019). The principle guiding this discussion is that technological efficiency is terrain-sensitive and context-dependent.

### Linking Investment, Logistics Efficiency, and Foundation Performance in Mountainous Terrain

This discussion is grounded in infrastructure economics and supply chain management theory. Adequate funding enables comprehensive geotechnical investigations, high-quality materials, and advanced construction technologies (Kulhawy & Mayne, 1990; Mehta & Monteiro, 2014). However, the translation of budget into performance outcomes is mediated by material logistics, particularly in mountainous terrain (Prakash et al., 2024; Hu et al., 2026; Miller & Stone, 2021). OECD (2023) emphasized that performance budgeting frameworks must link financial allocation to measurable outcomes. The principle here is that financial investment only translates into engineering success when mediated by logistics efficiency.

## METHODOLOGY

This study employs a narrative literature review methodology, a scholarly approach used to summarize and interpret existing research on a given topic. Unlike systematic reviews, which follow rigid protocols and quantitative synthesis, narrative reviews are flexible, descriptive, and interpretive, allowing researchers to weave together diverse sources into a coherent story of what is known, debated, and still uncertain. Sources were selected from Scopus, Web of Science, and Google Scholar, prioritizing peer-reviewed articles and reputable engineering reports to minimize bias. A limitation of this approach is its reliance on secondary sources, which may not capture unpublished Philippine case studies. Future empirical work is needed to validate these findings in local projects.

### Defining the Topic and Scope

The first step in conducting a narrative literature review is to define the topic and scope clearly. This involves formulating a research question or objective that guides the selection of sources. A well-defined scope ensures that the review is focused yet broad enough to capture multiple perspectives. For example, a review on "mechanized construction methods in mountainous terrain" would specify its boundaries—foundation works, cost efficiency, and terrain complexity—while excluding unrelated aspects of construction.

**Searching the Literature**

Once the topic is defined, the next step is to search for relevant literature. Narrative reviews do not require exhaustive searches like systematic reviews, but they should still be comprehensive enough to capture influential works. Researchers typically use databases such as Scopus, Web of Science, and Google Scholar, employing keywords and Boolean operators to refine results. Juntunen and Lehenkari (2019) emphasize that narrative reviews often prioritize breadth and representativeness over strict inclusion criteria, ensuring that seminal works and diverse viewpoints are included.

**Selecting and Analyzing Sources**

After gathering literature, researchers must select and analyze key studies. Unlike systematic reviews, which rely on rigid inclusion/exclusion protocols, narrative reviews allow judgment-based selection. Sources are evaluated for credibility, relevance, and contribution to the topic. Narrative reviews are interpretive, requiring researchers to synthesize findings into themes rather than simply listing them. This stage involves identifying patterns, contradictions, and gaps in the literature, which later form the thematic backbone of the review.

**Structuring the Review**

A narrative literature review is typically organized into thematic or chronological sections. A standard structure includes: (1) Introduction – defining the topic, scope, and rationale. (2) Background – providing theoretical or historical context. (3) Thematic sections – organizing literature into categories such as methods, outcomes, or debates. (4) Discussion – interpreting findings, highlighting strengths and weaknesses, and identifying gaps. (5) Conclusion – summarizing insights and suggesting directions for future research.

**Writing Critically and Integratively**

The writing style of a narrative review should be critical, integrative, and interpretive. Rather than summarizing each study in isolation, the reviewer compares and contrasts findings, highlighting agreements, disagreements, and methodological differences. For example: "Hu et al. (2026) demonstrated that construction delays due to poor logistics eroded the benefits of higher budgets, confirming that financial allocation alone is insufficient without logistical efficiency." Such a synthesis shows how individual studies contribute to broader debates.

**Revising and Acknowledging Limitations**

The final step is to revise, refine, and acknowledge limitations. Narrative reviews are inherently subjective, as they rely on the researchers' judgment in selecting and interpreting sources. Juntunen and Lehenkari (2019) caution that narrative reviews may suffer from selection bias or incomplete coverage.

**AI Policy**

In the preparation of this manuscript, the authors utilized Microsoft Copilot (AI-assisted tool) to support specific aspects of academic writing and research. The tool was employed for: improving clarity, grammar, readability of the text, ensuring compliance with journal requirements (APA 7th edition, structure, and section placement), assisting in the synthesis of literature and presentation of methodological frameworks.

## RESULTS AND DISCUSSION

The performance of transmission line foundations in mountainous terrain is shaped by multiple interdependent factors. This chapter presents the consolidated findings for each hypothesis, drawing on geotechnical theory, construction management studies, and contemporary case evidence. The discussion is organized thematically across five hypotheses: terrain characteristics, foundation type, geotechnical assessment, construction method, and budget allocation.

**The Influence of Slope Gradient and Soil Type on Transmission Line Foundation Performance**

Slope gradient alters the stress state experienced by foundations, reducing safety factors as angles increase (Terzaghi, 1943; Bromhead, 1992). Hu et al. (2026) confirmed that steep slopes amplify tower instability under rainfall, while Alkahtani (2025) demonstrated that slope ratios directly affect transmission tower safety. Soil type compounds risks: expansive clays undergo swelling and shrinkage cycles (Chen, 1988; Holtz & Kovacs, 1981), loose sands pose liquefaction hazards (Kramer, 1996; Seed & Idriss, 1971), and collapsible soils such as loess cause sudden settlements (Barden et al., 1973). The combined influence of slope geometry and soil strength jointly controls erosion and hydrologic hazards (Megahan et al., 2001; Rotaru et al., 2022).

Quantitative studies show hillside projects on plastic clays have failure rates four times higher than those on stable ground (Graterol, 2008). Hu et al. (2026) reported that repair costs for slope-related failures often exceed 50% of initial construction costs. Halpin and Woodhead (1998) identified geotechnical challenges as leading causes of delays, while Miller et al. (2021) found that mountainous projects experienced 15–25% longer foundation phases due to logistics. Mitigation strategies include comprehensive geotechnical investigations (Hussaina et al., 2022), reinforcement measures such as anti-slide piles (Alkahtani, 2025), adaptive foundation design (Díaz, 2023), ground improvement (Sabatini et al., 1999), and sustainable practices integrating slope stability with environmental preservation (Rotaru et al., 2022).

**Anchor Foundations and Construction Time Efficiency Compared to Pad and Pile Foundations**

Anchor foundations provide rapid installation and immediate load capacity, minimizing excavation and curing time (Acidri, 2019; Chandra Sekhar & Duggal, 2019). Crux Subsurface, Inc. (2022) found that anchor systems accelerate early construction phases by eliminating mass concrete pours. Pad foundations, while effective in stable soils, require extensive excavation and curing (Das & Sobhan, 2013). Pile foundations, indispensable in weak soils, demand specialized equipment and longer installation cycles (Hannigan et al., 2006; Reese et al., 2025).

Comparative studies confirm that anchor foundations outperform pad and pile foundations in accessible sites, but pad and pile foundations remain necessary in challenging geotechnical contexts. Acidri (2019) documented longer construction phases in Uganda's Karuma Interconnection Project due to prescriptive pile designs compared to adaptive anchor systems. Kandaris et al. (2018) emphasized that foundation selection must balance engineering needs with environmental and economic considerations. Chan and Kumaraswamy (2002) highlighted that anchor installation sequences are simpler, leading to improved crew productivity compared to pad and pile systems.

Accessibility amplifies these differences. Anchor foundations utilize small, track-mounted drilling rigs requiring minimal clearance, enabling rapid mobilization and lean material supply chains (Hannigan et al., 2006; Sabatini et al., 1999). In contrast, pad and pile foundations require heavy equipment access, wide staging areas, and continuous concrete supply (Reese et al., 2025). Hu et al. (2026) confirmed that adverse geotechnical conditions and poor accessibility introduce massive schedule variance. Mitigation strategies include hybrid approaches combining anchors with shallow pads (Acidri, 2019), preconstruction planning to enhance site accessibility (Miller et al., 2021), adaptive design based on terrain-sensitive assessments (Kandaris et al., 2018), and early geotechnical investigation to confirm anchor suitability (Poulos, 2017).

**The Role of Assessment Quality and Communication in Reducing Foundation Failure Rates**

High-quality geotechnical assessments are positively associated with lower foundation failure rates. Peck (1969) and Fellenius (2017) emphasized that insufficient exploration scope is a primary cause of unexpected failures. Hussaina et al. (2022) confirmed that accurate parameter assessment is essential for predicting bearing capacity, while Aruna & Arulselvan (2017) identified inadequate investigation as a recurring cause of distress.

Communication between design and field teams mediates the benefits of geotechnical assessments. SAALG (2025) and Saalg (2025) noted that miscommunication often leads to misaligned assumptions, while effective collaboration ensures that geotechnical insights are translated into practical construction strategies. Nova Group Pacific (2025) reinforced the importance of geotechnical engineering assessments as critical for construction projects, emphasizing that their value depends on integration into design and execution.

Forensic studies of foundation failures consistently attribute problems not to design flaws but to inadequate site characterization. Kulhawy and Mayne (1990) argued that estimating soil properties conservatively is critical to avoid unexpected failures. Fellenius (2017) highlighted that steep sites require extended subsurface exploration, and Miller et al. (2021) found that mountainous projects experienced longer foundation phases due to logistics. These findings validate the hypothesis that higher-quality assessments reduce failure rates, enhanced by strong communication.

**Mechanized Construction Methods and Cost Efficiency in Foundation Installation**

Mechanized construction methods—using cranes, drilling rigs, and automated equipment—have transformed foundation installation by reducing labor costs, accelerating schedules, and improving precision (Liu & Tian, 2024). Alsanabani et al. (2023) showed that mechanized approaches aligned with value engineering principles optimize both cost and sustainability.

However, mechanization's benefits are terrain-dependent. In moderate terrains, mechanization thrives due to ease of mobilization and high utilization rates. In highly rugged zones, logistical challenges, equipment breakdowns, and weather disruptions erode its cost advantage (Hu et al., 2026; Shahbazi et al., 2019). Illingworth (2000) emphasized that construction methods must adapt to terrain constraints, while Liu and Tian (2024) analyzed foundation selection for the mechanized construction of ultra-high voltage transmission lines, confirming terrain dependency.

Case studies highlight that mechanization reduces labor costs and accelerates schedules in moderate terrains but loses advantage in rugged zones. Alsanabani et al. (2023) confirmed that mechanized approaches aligned with sustainability principles optimize both cost and environmental outcomes. Shahbazi et al. (2019) documented equipment failure rates and costs in challenging terrains, reinforcing the hypothesis that mechanized methods improve cost efficiency primarily in terrains of moderate complexity.

### Linking Investment, Logistics Efficiency, and Foundation Performance in Mountainous Terrain

Adequate budget allocation enables comprehensive geotechnical investigations, high-quality materials, and advanced construction technologies. Mehta & Monteiro (2014) highlighted that investment in high-performance concrete improves durability, while Kulhawy & Mayne (1990) argued that conservative design requires sufficient budgetary support.

However, the translation of budget into performance outcomes is mediated by material logistics, particularly in mountainous terrain. Prakash et al. (2024) emphasized that supply chain efficiency is critical in such environments, while Hu et al. (2026) showed that poor logistics erode the benefits of higher budgets. Similarly, Philippine transmission projects in Cordillera provinces have faced cost overruns due to limited road access and difficult terrain, underscoring the importance of logistics efficiency in local contexts. Golder Associates (2016) confirmed that pipeline foundations in rugged terrain required both adequate funding and efficient logistics to achieve cost efficiency.

OECD (2023) reinforced the importance of performance budgeting frameworks, emphasizing that financial allocation must be linked to measurable outcomes. Nova Group Pacific (2025) highlighted those geotechnical assessments require adequate funding to be effective, but their value depends on integration into design and execution. These findings validate the hypothesis that greater budget allocation improves outcomes only when mediated by logistics efficiency.

## CONCLUSION

Interdependence of Terrain and Foundation Strategies. The results confirm that steep slopes and unstable soils significantly reduce foundation performance, leading to higher failure rates and construction delays. Anchor foundations provide time efficiency advantages in accessible terrains, while mechanized methods improve cost efficiency primarily in moderate terrain. However, these benefits diminish in rugged zones where logistics and mobilization challenges dominate. This demonstrates that terrain characteristics, foundation type, and construction method are interdependent variables that must be considered holistically in transmission line foundation design.

Critical Role of Geotechnical Assessment and Budget Allocation. High-quality geotechnical assessments, when coupled with effective communication between design and field teams, reduce failure rates and improve reliability. Similarly, greater budget allocation enhances outcomes only when mediated by efficient material logistics in mountainous terrain. These findings highlight that financial investment and technical rigor alone are insufficient unless supported by robust logistical planning, making logistics efficiency the key mediator in translating resources into performance.

## TRANSLATIONAL RESEARCH

In Philippine mountainous projects, integrating geotechnical assessment with logistics planning can directly inform government infrastructure programs such as the National Grid expansion. This study's findings can be applied beyond academic theory. Insights may inform Department of Energy guidelines on transmission line construction, training modules for civil engineering students, and industry standards for logistics planning in rugged terrain. These applications connect the theoretical contributions of this review to practical outcomes in Philippine infrastructure development.

## DIRECTIONS FOR FURTHER RESEARCH

Integrated Predictive Modeling of Terrain and Logistics. Future research should develop predictive models that integrate slope gradient, soil type, and logistical constraints to forecast foundation performance outcomes. Such models could combine geotechnical parameters with supply chain simulations, enabling proactive design and budgeting strategies tailored to mountainous terrain.

Empirical Case Studies on Mechanization and Logistics Efficiency. While current literature supports mechanization's efficiency in moderate terrains, more empirical case studies are needed to quantify its cost-benefit trade-offs in rugged zones. Longitudinal studies comparing projects with varying levels of mechanization and logistics investment would provide clearer evidence on how budget allocation and technology adoption interact to influence foundation reliability and cost efficiency.

## ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the Polytechnic University of the Philippines for providing academic and technical resources that facilitated this study. We also extend our appreciation to colleagues and peers who offered constructive feedback during the preparation of this manuscript. Special thanks are due to the research librarians and database specialists who assisted in literature retrieval. Finally, we recognize the broader academic community whose published works formed the foundation of this narrative review.

## COMPLIANCE STATEMENT

### Author Contributions

Nayna B. Mallopa—Conceptualization, Methodology, Writing; Angelene Francisco, Millen Grace Galero, And Vanessa Gallardo—Data Curation

### Originality and Plagiarism Declaration

This manuscript is an original work prepared by the authors and has not been submitted to nor published in any other journal. All sources have been properly cited in accordance with APA 7th edition guidelines, and the authors affirm that the paper complies with JPAIR's plagiarism standards.

### Conflict of Interest

The authors declare that there are no financial, institutional, or personal conflicts of interest that could have influenced the outcomes of this study.

### Funding Disclosure

No external funding was received for the completion of this research. The study was conducted independently, with resources provided by the authors' respective institutions.

### Ethical Considerations

This study is based entirely on secondary literature and does not involve human participants, experiments, or proprietary datasets. Ethical compliance is ensured through proper attribution, transparency of methods, and adherence to academic integrity standards.

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