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Review Article

The Effects of Seismic Behavior on High Ground Stress Soft Rock Tunnel: A Review

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Abstract

The purpose of this review is to critically assess seismic activity's effects on soft rock tunnels under high ground stress scenarios. The paper seeks to identify key novelties and research gaps in the existing literature, offering new insights into analytical techniques, excavation methods, support systems, and monitoring technologies. A comprehensive review of recent studies was conducted, focusing on seismic behavior, analytical techniques, and mitigation strategies for soft rock tunnels. Case studies were selected based on their relevance to high ground stress conditions and their contribution to understanding seismic resilience. Significant findings include the identification of specific geological conditions that exacerbate seismic risks and the comparative effectiveness of various analytical techniques and support systems. Novel insights into the interaction of structural reinforcements and monitoring systems are also discussed. The review highlights new analytical techniques and advanced monitoring systems that improve predictive accuracy and early detection of seismic risks. It also proposes a refined approach to integrating mitigation strategies for enhanced tunnel resilience.

Keywords: High Ground Stress; Seismic Behavior; Soft Rock Tunnel; Seismic Assessment; Tunnel Structure.

1. Introduction

The stability of soft rock tunnels under seismic conditions, particularly in high ground stress environments, is a critical concern for civil and geotechnical engineers. The interaction between seismic forces and geological conditions can significantly impact tunnel performance and safety. Despite substantial advancements in the field, there remains a need for a more integrated understanding of these interactions to improve risk management and mitigation strategies. Soft rock tunnels are constructed in a variety of geological settings, including sedimentary rocks, shale, and claystone, which exhibit distinct mechanical and deformation characteristics. High ground stress conditions further complicate tunnel stability, as increased pressure can lead to significant deformation and failure under seismic loading [1]. The seismic behavior of these tunnels is influenced by several factors, including rock composition, stress conditions, excavation techniques, and support systems.

Previous Studies:

- *Seismic Impact on Tunnels*: Studies such as those by Jaramillo (2017) [2] have investigated the effects of seismic activity on tunnel stability, focusing on tunnels in various geological settings. They found that the impact of seismic forces can be exacerbated by high ground stress, leading to more severe deformation and potential failure.
- *Geological Conditions*: Research by Wang et al. (2019) [3] highlighted the importance of understanding geological

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conditions in seismic analysis. They identified specific rock formations that are particularly vulnerable to seismic damage, such as highly fractured or weakly cemented rocks.

- *Analytical Techniques*: The work of Asheghabadi & Matinmanesh (2011) [4] reviewed various analytical methods for seismic assessment, including Finite Element Analysis (FEA) and Discrete Element Method (DEM). Their findings emphasized the need for accurate models that consider both seismic forces and high ground stress conditions.

Research Gaps and New Insights

While existing studies provide valuable insights, several research gaps persist:

- *Integration of High Ground Stress and Seismic Activity:* Many studies focus separately on high ground stress or seismic activity, without addressing their combined effects comprehensively. This gap underscores the need for integrated models that consider both factors simultaneously.
- *Comparative Analysis of Analytical Techniques:* Although various analytical methods are available, there is limited comparative analysis of their effectiveness in predicting tunnel behavior under combined high ground stress and seismic loading.
- *Effectiveness of Support Systems and Monitoring Technologies:* There is a need for more detailed evaluations of different support systems and monitoring technologies, especially in terms of their combined effectiveness in mitigating seismic risks.

Proposed Approach

To address these gaps, this review proposes a multi-faceted approach that includes:

- *Enhanced Theoretical Models:* Developing and applying advanced theoretical models that integrate high ground stress and seismic activity. This approach will improve the accuracy of predictions and the effectiveness of mitigation strategies.
- *Case Study Analysis:* Utilizing real-world case studies to evaluate the performance of different excavation techniques, support systems and monitoring technologies under seismic conditions.
- *Comparative Analysis:* Conducting a comparative analysis of analytical techniques to determine the most effective methods for seismic assessment and prediction.

Structure of the Article

- *Literature Review:* A detailed overview of existing research, focusing on seismic impacts, geological conditions and support systems.
- *Theoretical Approaches:* Discussion of current theoretical models and their relevance to high ground stress and seismic behavior.
- *Analytical Techniques:* Comparative analysis of different methods used in seismic assessment, including their strengths and limitations.
- *Excavation Techniques:* Examination of various excavation methods and their impact on tunnel resilience under seismic loading.
- *Support Systems:* The efficiency of various support methods including shotcrete, flexible linings and rock bolts, in boosting seismic resistance is evaluated.
- *Monitoring Technologies:* Review of advanced monitoring systems and their role in early detection and risk management.
- *Mitigation Strategies:* Analysis of integrated mitigation approaches, including the interaction between structural reinforcements and monitoring systems.
- *Conclusion:* An overview of the main conclusions and suggestions for more study.

2. Seismic Behavior of Tunnels in Soft Rock

Tunnels excavated in soft rock under high ground stress are particularly vulnerable to seismic forces due to the combination of weak rock material and significant stress concentrations. Understanding the seismic behavior of these tunnels is crucial for designing effective support systems and ensuring long-term stability [5]. The complex interplay between seismic waves, rock mass properties and tunnel structures necessitate a comprehensive analysis to mitigate potential risks. The seismic behavior of tunnels in soft rock is of paramount importance for several reasons:

- *Safety:* Ensuring the safety of personnel and infrastructure within and around the tunnel.
- *Economic Impact:* Preventing costly repairs and downtime resulting from seismic damage.
- *Design Optimization:* Informing the design of more resilient support systems that can withstand seismic forces.

2.1. Geotechnical Characteristics of Soft Rock

Understanding the geotechnical characteristics of soft rock is fundamental to assessing the seismic behavior of tunnels. Soft rocks such as claystone, mudstone and shale, are distinguished by their low strength and high deformability, which can significantly influence their response to seismic forces.

Mechanical Properties of Soft Rock

Soft rocks are characterized by a range of mechanical properties that affect their stability under seismic loading. Shear strength, Poisson's ratio, modulus of elasticity and uniaxial compressive strength (UCS) are some of these characteristics [6, 7]. These characteristics are summarized for popular varieties of soft rock in Table 1.

Table 1. Mechanical properties of common soft rocks

Rock Type	UCS (MPa)	Modulus of Elasticity (GPa)	Poisson's Ratio	Shear Strength (MPa)
Claystone	10 – 30	1 – 5	0.25 – 0.35	5 – 15
Mudstone	5 – 25	0.5 – 3	0.20 – 0.30	2 – 10
Shale	15 – 40	3 – 10	0.20 – 0.35	10 – 20

Soft rock is affected by these characteristics under both static and dynamic stresses. For instance, soft rock is prone to severe deformation under load, which can be made worse by seismic occurrences, as shown by the low UCS and modulus of elasticity [8].

Anisotropy and Heterogeneity

Soft rocks often exhibit anisotropic and heterogeneous properties, meaning their mechanical behavior can vary significantly in different directions and locations. Anisotropy can be caused by joints, fissures and bedding planes, among other things. These characteristics may cause stress concentration and differential deformation, which might compromise the overall stability of tunnels.

Effects of High Ground Stress

Conditions of high ground stress, which are frequently seen in deep tunnels, make soft rock more difficult to work with. The combination of seismic forces and in-situ stress affects the distribution of stress surrounding a tunnel [9, 10]. The following equations describe the stress distribution in a cylindrical tunnel:

$$\sigma_r = \frac{\sigma_0}{2}\left(1-\frac{r_0^2}{r^2}\right)+\frac{\Delta P}{2}\left(1+\frac{r_0^2}{r^2}\right)\cos(2\theta) \tag{1}$$

$$\sigma_\theta = \frac{\sigma_0}{2}\left(1+\frac{r_0^2}{r^2}\right)-\frac{\Delta P}{2}\left(1+\frac{3r_0^2}{r^2}\right)\cos(2\theta) \tag{2}$$

$$\tau_{r\theta} = -\frac{\Delta P}{2}\left(1+\frac{r_0^2}{r^2}\right)\sin(2\theta) \tag{3}$$

where: σ_r and σ_θ are the radial and tangential stresses, respectively. $\tau_{r\theta}$ is the shear stress, σ_0 is the far-field stress, ΔP is the pressure difference caused by seismic waves, r and θ are the polar coordinates, r_0 is the radius of the tunnel.

Understanding the geotechnical characteristics of soft rock is essential for assessing the seismic behavior of tunnels. The mechanical properties, anisotropy, time-dependent behavior, and effects of pore water pressure and high ground stress all play critical roles in determining tunnel stability.

2.2. Seismic Wave Interaction

Seismic wave interaction with tunnels in soft rock is a critical aspect of understanding the seismic behavior of these structures. Effective design and safety precautions depend on an understanding of the interaction between seismic waves and tunnel structures, which affects the tunnel's stability and deformation.

2.2.1. Seismic Wave Propagation in Soft Rock

A. Wave Types and Characteristics

Primary waves (P-waves), secondary waves (S-waves), and surface waves (Love and Rayleigh waves) are the three types of seismic waves produced by earthquakes. Different wave types interact with soft rock and tunnel constructions in different ways (Figure 1).

- *P-Waves:* These compressional waves alter the volume of the rock by traveling quicker than S-waves. They have the ability to significantly alter the tunnel's structure's stress.
- *S-Waves:* These are shear waves that move slower than P-waves and cause horizontal and vertical shearing in the rock. S-waves are particularly impactful on tunnel stability due to their shearing action.
- *Surface Waves:* As a result of their high amplitude and low frequency, these waves typically cause the most damage as they travel along the Earth's surface. Love waves cause horizontal shearing while Rayleigh waves induce both vertical and horizontal displacements.

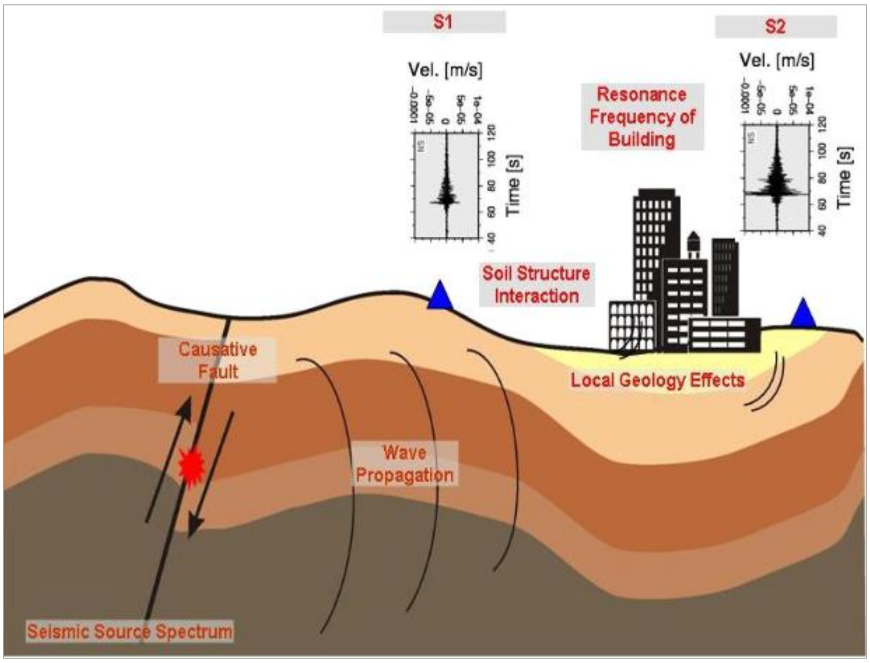

Figure 1. Seismic wave propagation through soft rock [11]

2.2.2. Interaction with Tunnel Structures

Stress and Strain Induced by Seismic Waves

Seismic waves induce dynamic stresses and strains in tunnel structures, which can lead to deformation, shear failure or even collapse. The interaction can be analyzed using the following equations:

Dynamic Stress: The dynamic stress (σ_d) induced by seismic waves can be expressed as:

$$\sigma_d = \sigma_{max} \times \sin(\omega t) \tag{4}$$

where: σ_{max} is the maximum stress, ω is the angular frequency of the seismic wave, t is time.

Strain Response: The strain (ϵ) in the tunnel due to seismic loading can be calculated using:

$$\epsilon = \frac{\sigma_d}{E} \tag{5}$$

where E is the modulus of elasticity of the rock.

Effects of Tunnel Shape and Orientation

The shape and orientation of a tunnel significantly influence its seismic response. Circular and horseshoe-shaped tunnels generally perform better under seismic loading compared to rectangular or irregular shapes. The stability of the tunnel is also influenced by its orientation with respect to the direction in which seismic waves propagate [12]. Circular tunnels exhibit more uniform stress distribution and reduced stress concentration at the tunnel face, making them more resilient to seismic forces while rectangular tunnels often experience higher stress concentrations at the corners and faces, leading to increased risk of failure under seismic loading (see Table 2).

Table 2. Comparative analysis of tunnel shapes

Tunnel Shape	Stress Concentration	Deformation Response	Suitability for Seismic Conditions
Circular	Low	Uniform	High
Rectangular	High	Non-uniform	Low

Understanding the interaction between seismic waves and tunnel structures in soft rock is crucial for designing resilient tunnels capable of withstanding seismic events. Advances in numerical modeling, monitoring technologies and smart materials offer new insights and solutions for improving tunnel stability. Accurate prediction and analysis of seismic wave interaction with tunnel structures enable better design and safety measures, ensuring the longevity and safety of tunnel infrastructure in seismically active regions.

2.3. Deformation and Failure Mechanisms

Understanding the deformation and failure mechanisms in tunnels constructed in soft rock under seismic loading is crucial for designing robust support systems and ensuring safety. The interaction between seismic forces and soft rock can lead to various types of deformations and failure patterns, which can significantly impact tunnel stability.

2.3.1. Deformation Mechanisms in Soft Rock Tunnels

Elastic Deformation

In the initial stages of seismic loading, soft rocks exhibit elastic deformation, where the rock and tunnel lining deform proportionally to the applied stress. This deformation is reversible upon the removal of seismic loads. The elastic behavior of soft rock is characterized by its modulus of elasticity (E), which can be estimated from laboratory tests. For soft rocks, E ranges from 0.5 to 10 GPa. The equation for elastic deformation is:

$$\epsilon = \frac{\sigma}{E} \tag{6}$$

where: ϵ is the strain, σ is the stress, E is the elastic modulus.

Plastic Deformation

Beyond the elastic limit, soft rocks undergo plastic deformation, where permanent changes in shape occur. Constitutive models like the Drucker-Prager or Mohr-Coulomb models describe this kind of deformation, which is characterized by yielding (Table 3). The beginning of plastic deformation and failure in rocks is described by the Mohr-Coulomb Failure Criterion.

$$\tau = c + \sigma \cdot \tan(\phi) \tag{7}$$

where, σ is the normal stress, ϕ is the internal friction angle, c is the cohesiveness and τ is the shear stress.

Table 3. Key parameters for elastic and plastic deformation

Parameter	Elastic Deformation	Plastic Deformation
Young's Modulus (E)	Determines stiffness and initial deformation	Affects post-yield behavior
Poisson's Ratio (v)	Controls lateral strain during deformation	Influences the extent of plastic flow
Yield Strength (σ_y)	Not applicable	Defines the transition from elastic to plastic

2.3.3. Failure Mechanisms

Shear Failure

When the shear stress is greater than the rock mass's shear strength, shear failure happens. In soft rocks, shear failure can be particularly problematic due to their low shear strength. Shear failure often develops along predefined failure surfaces or planes, influenced by the orientation of natural fractures or joints (Figure 2).

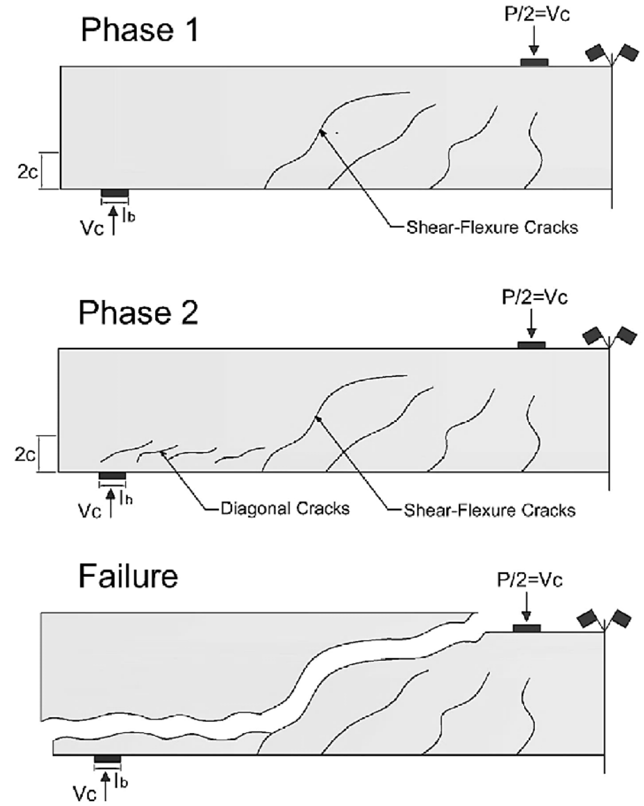

Figure 2. Shear failure mechanism [13]

Tensile Failure

When the rock's tensile strength is exceeded by the tensile stress, tensile failure happens. Although soft rocks generally have low tensile strength, tensile failure can occur, especially near the tunnel face or in areas with high stress concentrations. For soft rocks, tensile strength is often much lower than compressive strength, making tensile failure a critical concern. Tensile Failure Criterion is:

$$\sigma_t = \frac{F}{A} \tag{8}$$

where A is the cross-sectional area, F is the force producing the tensile stress, and σ_t is the tensile stress.

Buckling and Collapse

As a result of the combined effects of axial stresses and bending moments, soft rock tunnels may buckle or collapse under excessive seismic loading [14]. This is particularly relevant for shallow tunnels or those with inadequate support. Euler's formula for columns may be used to predict the critical buckling load for a tunnel. The Euler's Buckling Load is:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \tag{9}$$

where: L is the effective length of the tunnel; K is the column effective length factor; I is the cross-sectional moment of inertia; E is the modulus of elasticity and P_{cr} is the critical buckling load.

The deformation and failure mechanisms in tunnels constructed in soft rock under seismic loading involve complex interactions between material properties, stress conditions, and structural responses. Recent advancements in modeling and monitoring techniques have enhanced our understanding of these mechanisms, leading to more accurate predictions and improved design practices. By incorporating these insights, engineers can better anticipate and mitigate the effects of seismic loading on tunnel stability.

3. High Ground Stress Conditions

High ground stress conditions refer to scenarios where the stress exerted on a geological formation, such as rock or soil, is significantly elevated due to various factors including depth, tectonic forces and existing geological structures. These conditions are characterized by increased vertical and horizontal stresses that impact the stability and behavior of subsurface excavations, such as tunnels.

3.1. Components of Ground Stress

Ground stress is typically decomposed into three principal components:

- *Vertical Stress (σ_v):* This is the vertically downward tension caused by the weight of the rock mass above [15]. It increases with depth and is given by:

$$\sigma_v = \rho \cdot g \cdot h \tag{10}$$

where: h is the depth of the rock mass, ρ is the density of the rock and g is the acceleration caused by gravity (about 9.81 m/s²).

- *Horizontal Stresses (σ_h):* These are the stresses acting horizontally within the rock mass, which can be influenced by tectonic forces, existing geological structures, or variations in rock properties. Horizontal stresses can be further categorized into:

Maximum Horizontal Stress (σ_{h1}) and Minimum Horizontal Stress (σ_{h2})

The ratio of these stresses relative to vertical stress is often used to evaluate the stress regime.

- *Principal Stresses:* At a certain location within the rock mass, they are the maximum and minimum normal stresses. They are given by:

$$\sigma_1 \geq \sigma_2 \geq \sigma_3 \tag{11}$$

The maximal main stress is represented by σ_1, the intermediate principal stress by σ_2 and the least principal stress by σ_3 (see Table 4).

Table 4. Typical ground stress parameters

Stress Type	Formula	Typical Range
Vertical Stress (σ_v)	$\rho \cdot g \cdot h$	10 – 100 MPa (depending on depth)
Maximum Horizontal Stress (σ_{h1})	Variable, influenced by tectonic forces	5 – 50 MPa
Minimum Horizontal Stress (σ_{h2})	Variable, often less than (σ_{h1})	2 – 30 MPa
Principal Stresses (σ_1, σ_2, σ_3)	Calculated from stress measurements	Up to 150 MPa

3.2. Implications of High Ground Stress Conditions

The design, building and safety of tunnels and other subterranean structures are significantly impacted by high ground stress conditions. These ramifications fall under a few main categories:

Impact on Tunnel Stability

- *Increased Risk of Deformation:* Significant deformation of the surrounding rock mass and tunnel lining can be caused by high ground stress. This deformation can manifest as tunnel convergence, which is the reduction in tunnel diameter due to rock squeezing.

$$\Delta d = \frac{\sigma_{int} - \sigma_{ext}}{E} \tag{12}$$

where: Δd is the change in diameter, σ_{int} is the internal stress, σ_{ext} is the external stress, E is the elastic modulus of the rock.

- *Increased Likelihood of Rock Failure:* Failure mechanisms such shear failure, tensile failure, or the development of new fractures may be brought on by the excessive stress. This failure can compromise the integrity of the tunnel and pose safety risks.

Ground Support and Reinforcement

- *Design of Support Systems:* Tunnels in high stress conditions require robust support systems including rock bolts, shotcrete and steel sets, to counteract the increased loads and potential for rock failure [16]. Static and dynamic loading conditions need to be taken into consideration in the design.
- *Rock Bolting:* High-stress environments may require longer and more frequent rock bolts to effectively stabilize the tunnel.
- *Shotcrete:* Enhanced shotcrete applications with increased thickness or reinforced with fibers may be needed to provide adequate support.

- *Monitoring and Maintenance:* Continuous monitoring of stress levels, deformations and potential failures is essential for ensuring tunnel stability and safety. Advanced monitoring techniques such as fiber-optic sensors and real-time data acquisition systems, are increasingly employed.

Groundwater Interactions

- *Impact of Groundwater:* High ground stress conditions can be exacerbated by the presence of groundwater. Water infiltration can increase pore pressure, reduce effective stress and contribute to instability.
- *Hydrostatic Pressure Effects:* Groundwater can exert additional hydrostatic pressure on tunnel linings, influencing design considerations and support requirements.

Tunnel design and construction must take into account high ground stress conditions. For subterranean constructions to be safe and effective, it is crucial to comprehend the elements of ground stress, their consequences for tunnel stability, and new developments in measurement and modeling approaches [17]. By integrating these insights into design practices and utilizing advanced technologies, engineers can better manage high stress conditions and mitigate associated risks.

3.3. Stress Distribution and Concentration

Understanding the behavior of tunnels under high ground stress levels requires an understanding of stress concentration and distribution [18]. The way stress is distributed around and within a tunnel affects its stability and performance. Stress concentration, in particular, can lead to localized areas of high stress, increasing the risk of deformation and failure.

3.3.1. Principles of Stress Distribution

A. Stress Distribution Around a Tunnel

The characteristics of the surrounding rock mass and the applied loads control how stress is distributed around a tunnel [14]. Important elements affecting the distribution of stress include:

- *Rock Properties:* The distribution of stresses is dependent on the rock's elastic modulus, Poisson's ratio, and shear strength [19]. These properties are critical in determining the deformation behavior of the tunnel.
- *Tunnel Shape and Size:* The geometry of the tunnel (circular, horseshoe-shaped, etc.) affects stress distribution. For instance, circular tunnels generally result in a more uniform stress distribution compared to non-circular shapes.
- *Excavation Sequence:* The sequence and method of excavation (e.g., sequential excavation, full-face excavation) impact how stresses are redistributed around the tunnel.

B. Analytical Methods for Stress Distribution

Analytical methods for determining stress distribution around tunnels include:

Terzaghi-Wegman Solution: The stress distribution for a circular tunnel in an elastic material is provided by this traditional solution [20]:

$$\sigma_r = \sigma_0\left(1 - \frac{R^2}{r^2}\right) \tag{13}$$

where: R is the tunnel radius, r is the radial distance from the tunnel center, σ_r is the radial stress and σ_0 is the initial stress [21].

Wegman's Solution: Extends Terzaghi's solution to account for non-circular tunnels and varying boundary conditions.

3.3.2. Stress Concentration

Stress concentration occurs when the applied stress exceeds the average stress in a particular region, often due to geometric irregularities, changes in rock properties, or excavation methods (Figure 3). Key causes and effects include:

- *Geometric Irregularities:* Sharp corners or abrupt changes in tunnel geometry can lead to localized stress concentrations. For example, the intersection of two tunnels can create high-stress zones.
- *Rock Discontinuities:* Existing faults or joints in the rock can lead to stress concentration and affect the stability of the tunnel.
- *Support Systems:* The interaction between support systems and the surrounding rock can create stress

concentrations, particularly at interface regions.

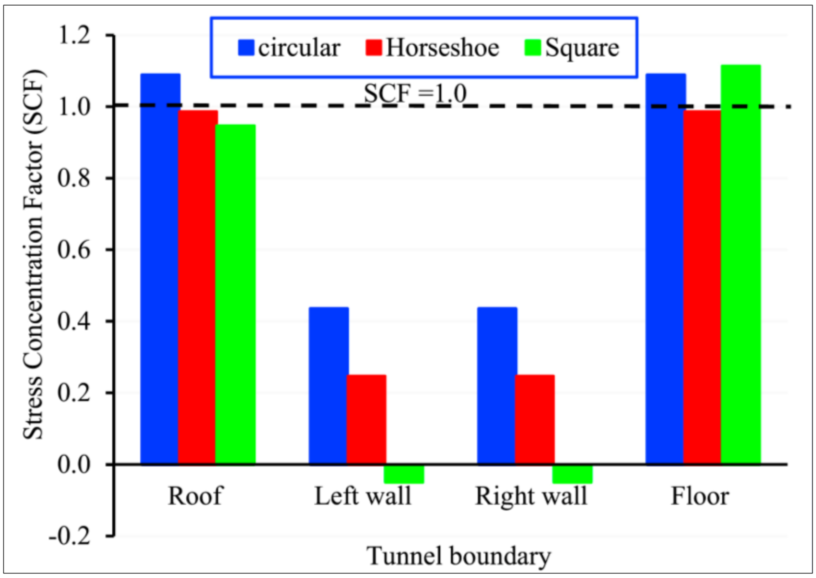

Figure 3. Stress concentration at tunnel boundary [22]

4. Seismic Behavior of High Ground Stress Soft Rock Tunnels

The stiffness of a tunnel, the type of ground motion and the tunnel's interaction with the surrounding soil are all significant determinants of a tunnel's seismic reactivity [23]. Due to its low stiffness and exposure to significant ground stress, soft rock tunnels are particularly prone to seismic damage. There are three types of tunnel responses to earthquake-induced ground motion: elastic, inelastic and failure. When the tunnel's stress stays within the elastic limit, elastic response happens. When the stress surpasses the elastic limit, an inelastic reaction happens causing the tunnel to deform plastically. Failure happens when the tunnel collapses because the tunnel's internal stress is greater than the rock's capacity to withstand it. Seismic investigation of a soft rock tunnel with significant ground stress must include determining the tunnel's reaction to different amounts of ground motion [24]. This is accomplished by accounting for the ground motion's features, the tunnel's stiffness, and the tunnel's interactions with the surrounding soil [25]. Numerous elements including as geological and geotechnical characteristics, excavation techniques and support systems have an impact on the seismic behavior of high ground stress soft rock tunnels. Here are some of the main elements influencing seismic behavior that are discussed:

4.1. Geological Conditions

In geological strata with low strength and high deformability under conditions of severe ground stress, soft rock tunnels are commonly built. Shale, claystone and poorly cemented sandstone are common soft rock types found in tunnel construction zones [26]. These formations have unique mechanical characteristics that affect how tunnels behave, particularly under conditions of severe ground stress. Significant overburden pressures applied to the tunnel walls define high ground stress conditions. Under such circumstances, tectonic activity, depth and geological structure all affect the stress distribution surrounding a tunnel [27]. Tectonic forces, overburden pressure, mining operations and other natural and artificial variables all affect the stress state in soft rock tunnels. Elevated ground stress levels may result in intricate stress distributions around the tunnel, hence impacting the stability and efficacy of the tunnel [28]. The possibility of failure mechanisms inside the rock mass, such as shear fracture, squeezing or spalling, is determined by the size and direction of the major stresses.

4.2. Excavation Techniques

High ground stress soft rock tunnels' seismic resistance is strongly influenced by the methods used during excavation. The stability of the rock mass, the growth of induced stresses, and the tunnel's overall safety are all impacted by the excavation method selection [29].

- *Conventional Drilling and Blasting:* Conventional drilling and blasting remain widely used for tunnel excavation due to their cost-effectiveness and versatility. However, these techniques can introduce significant stress concentrations and fragmentation in high ground stress conditions. Recent advancements focus on controlling blast-induced damage and stress redistribution. Sharafat et al. (2019) [30] introduced controlled blasting methods that minimize damage by optimizing blast parameters and employing pre-split blasting techniques. These methods help reduce stress concentrations around the tunnel. The equation for blast-induced stress redistribution is:

$$\Delta\sigma = \frac{Q}{4\pi r^2} \cdot e^{-\frac{r}{R}} \tag{14}$$

where $\Delta\sigma$ is the change in stress, Q is the blast energy, r is the distance from the blast center and R is the blast radius [30]. Fu et al. (2023) [31] developed new blasting techniques to control rock fragmentation, which improves the stability of the tunnel face and reduces the risk of rockbursts in high-stress conditions.

- *Tunnel Boring Machines (TBMs):* Tunnel Boring Machines (TBMs) offer a more controlled excavation process compared to conventional methods. They are particularly effective in managing ground stress and minimizing surface subsidence. Recent innovations in TBM design include advanced ground support systems and real-time monitoring. Wang et al. (2024) [32] introduced a new TBM equipped with adaptive ground support systems that adjust to varying stress conditions, enhancing tunnel stability. Huang et al. (2018) [33] implemented real-time monitoring systems in TBMs to track ground conditions and adjust excavation parameters dynamically. This approach improves safety and efficiency by allowing prompt adjustments to excavation strategies.

- *New Austrian Tunnelling Method (NATM):* The New Austrian Tunnelling Method (NATM) is a flexible excavation approach that uses sequential excavation and support to manage ground stress. It relies on monitoring and adjusting support as excavation progresses. Recent advancements in NATM include improved support systems that integrate shotcrete and rock bolts more effectively. Vitali et al. (2022) [34] developed a new NATM protocol that optimizes the timing and type of support based on real-time ground conditions. The equation for support optimization is:

$$S_{opt} = \frac{F_S \cdot (1 + \alpha \cdot R)}{B} \tag{15}$$

where S_{opt} is the optimized support, F_S is the support force, α is the adjustment factor, R is the ground resistance and B is the support spacing [34]. Aghajari et al. (2024) [35] explored advanced sequential excavation techniques that reduce the risk of instability by improving the timing of support installation and excavation.

- *Hydro-Mechanical Excavation:* Hydro-mechanical excavation methods, such as hydraulic fracturing and water jetting, are used to manage ground stress and reduce rock fragmentation (Figure 4). These techniques involve applying hydraulic pressure to fracture the rock. Recent research by Jiang et al. (2023) [36] improved hydraulic fracturing techniques by using high-pressure water jets combined with chemical additives to enhance rock fragmentation and reduce stress concentrations. The equation for hydraulic fracturing pressure is:

$$P_H = \frac{Q}{A + \sigma_r} \tag{16}$$

where P_H is the hydraulic pressure, Q is the water flow rate, A is the fracture area and σ_r is the rock stress [36]. Oh et al. (2013) [37] explored advanced water jetting techniques that improve the precision of rock fragmentation while minimizing the impact on surrounding rock masses.

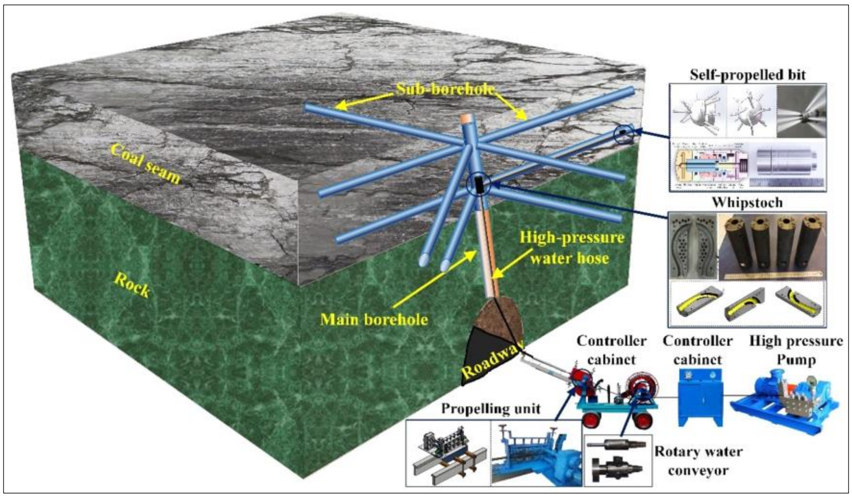

Figure 4. Hydraulic fracturing and water jetting process [38]

- *Sequential Excavation Method (SEM):* The Sequential Excavation Method (SEM) is a widely used technique for tunneling in challenging geological conditions. It involves excavating the tunnel in stages, allowing for controlled support installation and minimizing ground disturbance. Recent innovations in SEM include enhanced support systems tailored for high ground stress environments. Zeng et al. (2020) [39] introduced advanced steel fiber reinforced shotcrete and rock bolts that improve the stability of the tunnel face and surrounding rock mass during excavation. Ayvaz & Alpay (2021) [40] implemented real-time monitoring systems during SEM to adjust excavation parameters dynamically. Their approach uses data from ground sensors and automated systems to optimize excavation processes and enhance tunnel stability.

- *Cut and Cover Method:* The Cut and Cover Method involves excavating a trench from the surface, constructing the tunnel, and then covering it. This method is suitable for shallow tunnels and can be adapted for seismic conditions with appropriate reinforcement. Recent research by Nguyen et al. (2010) [41] developed reinforced cut and cover methods to improve seismic resilience. Their approach includes the use of reinforced concrete and steel mesh to enhance the tunnel's ability to withstand seismic forces. Park et al (2010) [42] introduced methods for evaluating seismic performance in cut and cover tunnels. Their approach uses seismic hazard analysis and dynamic loading simulations to assess the effectiveness of various reinforcement strategies. Recent advancements in excavation techniques have significantly improved the management of high ground stress conditions in soft rock tunnels. Controlled blasting techniques, innovations in Tunnel Boring Machines (TBMs), enhancements in the New Austrian Tunnelling Method (NATM), and advancements in hydro-mechanical excavation methods have all contributed to better stability and reduced seismic risks. By integrating these new techniques and technologies, engineers can enhance the safety and efficiency of tunnel excavation in challenging conditions.

4.3. Support Systems

Support systems are critical in enhancing the seismic resilience of tunnels, particularly in high ground stress soft rock conditions. These systems help to stabilize the tunnel, prevent collapse and mitigate the effects of seismic loading. This section explores recent advancements in support systems, highlighting new insights, significant findings and practical applications.

Rock Bolts: Rock bolts are a fundamental support system used to stabilize the rock mass surrounding tunnels. They are installed by drilling into the rock and then grouting or mechanically anchoring the bolts in place. Recent research by Ghorbani et al. (2020) [43] introduced high-strength rock bolts designed specifically for high ground stress conditions. These bolts are made from advanced materials that provide enhanced load-bearing capacity and durability under seismic loading. Shimamoto & Yashiro (2021) [44] developed pre-stressed rock bolts that enhance the initial stability of the tunnel. Their approach involves applying a pre-tension force to the bolts, which improves the overall stability and reduces the potential for deformation during seismic events.

Shotcrete: Shotcrete, a spray-applied concrete, provides immediate support to tunnel surfaces. It is often used in conjunction with other support systems to form a protective layer. Recent advancements include the use of fiber-reinforced shotcrete (FRS). According to Patnaik & Adhikari (2012) [45], incorporating steel or synthetic fibers into the shotcrete mix improves its tensile strength and ductility, enhancing its ability to resist seismic forces. Recent research by Zhang et al. (2022) [46] introduced self-healing shotcrete that can repair minor cracks autonomously. This type of shotcrete contains capsules of healing agents that activate when cracks form, improving long-term durability and reducing maintenance needs. Recent research by Ahmad et al. (2023) [47] developed high-performance shotcrete mixes that use advanced additives to improve adhesion and durability in seismic conditions.

Flexible Linings: Flexible linings, such as inflatable or fabric-based systems, are used to provide additional support and accommodate ground movements. These linings can be particularly useful in soft rock conditions where ground deformation is significant. Recent innovations include inflatable linings that can adjust to ground movements. According to Sosa et al. (2014) [48], these linings use inflatable bladders to conform to the tunnel shape, providing dynamic support that adapts to seismic activities. Paul et al. (2023) [49] developed advanced fabric-based linings that incorporate high-strength materials and polymer coatings to resist deformation and provide additional support. These linings are particularly effective in areas with high ground stress and seismic activity. Recent developments include advanced elastomeric linings that offer superior flexibility and durability. Kumar et al. (2014) [50] tested new elastomeric materials that provide enhanced seismic resistance and adaptability to ground movements. Petraroia et al. (2024) [51] introduced hybrid lining systems that combine elastomeric materials with traditional concrete. This combination provides both flexibility and structural strength, improving overall seismic performance.

Hybrid Support Systems: Hybrid support systems combine multiple support techniques to enhance stability and performance. These systems integrate rock bolts, shotcrete and flexible linings to provide comprehensive support. Recent research by Pandit & Babu (2021) [52] introduced hybrid support systems that combine rock bolts, fiber-reinforced shotcrete, and inflatable linings. Their study demonstrated that these integrated systems offer superior performance in terms of load distribution, deformation control, and seismic resilience. Wen et al. (2023) [53] developed optimization methods for hybrid support systems, using simulation and field testing to determine the most effective combinations of support techniques for different ground conditions and seismic scenarios.

Strut and Arch Systems: Strut and arch systems are used to provide additional support by transferring loads to stable ground areas. They are particularly useful in shallow tunnels and areas with variable ground conditions. Recent advancements include modular strut systems that can be easily adjusted and configured to fit different tunnel geometries. Krauze et al. (2021) [54] developed modular systems that enhance adaptability and reduce construction time. Recent research by Wu et al. (2022) [55] focused on optimizing arch designs for better load distribution and seismic performance. Their approach includes the use of high-strength materials and advanced design techniques. Advancements in support systems have significantly improved the ability to manage seismic risks and high ground stress conditions in soft rock tunnels. Innovations such as high-strength and pre-stressed rock bolts, fiber-reinforced and self-healing shotcrete, advanced inflatable and fabric-based linings and hybrid support systems offer enhanced stability and performance. These developments provide engineers with a range of options for designing and implementing effective support systems tailored to specific tunnel conditions and seismic requirements, ultimately contributing to safer and more resilient tunnel infrastructure.

5. Ground Motion Analysis

According to Hashash et al. (2001) [56], a ground motion is defined as a time history of acceleration, velocity, or displacement with three crucial parameters: amplitude, frequency content and duration of strong ground motion. The type of analytical technique used in the design will determine which kind of ground motion parameters are required. Three translational components—longitudinal, transverse and vertical with respect to the tunnel axis—are often used to characterize ground movements. For the seismic engineering of underground tube systems, determining the seismic design earthquake or earthquakes, appropriate ground motion levels, and other associated seismic risks is an essential effort. Seismic hazard analysis is the process of figuring out the design ground motion parameters for a seismic analysis. The features of the earthquake source, attenuation relationships, and historical earthquake data are crucial components for seismic hazard assessments [57]. The strength of an earthquake's ground motion is determined by several critical factors such as peak acceleration, peak velocity, peak displacement, response spectrum, duration and others [58, 59]. Peak ground velocity (PGV) is as important as peak ground acceleration (PGA) for seismic design and analysis of subterranean structures, including tunnels, as it may be used to quantify ground stresses or the difference in displacement between two sites in the earth [60]. Peak ground acceleration is often not an appropriate metric for earthquake design in subterranean constructions such as tunnels because tube constructions are more susceptible to ground distortions than to inertial forces. Peak speed and acceleration can be found using empirical techniques, field measurements or site-specific seismic exposure research [58].

6. Seismic Hazard Analysis

To determine the amount of shaking and the planned earthquake or earthquakes for an underground facility, a seismic hazard study is utilized. Three fundamental methods are used in seismic hazard studies to determine the likelihood of significant ground motions: the amount of active faulting present at a place, the likelihood that a fault will move, and the frequency at which the faults release stored energy [56]. Seismic hazards are defined as the possibility that an earthquake may occur at a given place, at a certain time, and with ground motion intensity higher than a predetermined threshold [61]. The first seismic hazard calculations were developed by C. Allen Cornell in 1968 and they may be extremely sophisticated depending on their level of significance and application [62, 63]. There are two methods of analysis [56]:

- The DSHA (Deterministic Seismic Hazard Analysis) and;
- The PSHA (Probabilistic Seismic Hazard Analysis).

6.1. Deterministic Seismic Hazard Analysis

To evaluate the ground motion risk at a site, a deterministic seismic hazard assessment constructs a specific seismic scenario [64]. A seismologist first determines the maximum magnitude for each possible seismic source in a deterministic seismic hazard study [60]. Deterministic seismic hazard analysis involves simulating a specific seismic event, or an earthquake of a certain magnitude at a specific location, in order to discover all the dangers related to ground motion. The worst-case possibilities for a site may be easily assessed using a deterministic seismic hazard analysis. But according to Hung et al. (2009) [60] and Hashash et al. (2001) [56], neither the likelihood nor the frequency of the controlling earthquake's recurrence is included.

6.2. Probabilistic Seismic Hazard Analysis

The core idea behind probabilistic seismic hazard analysis is that future seismicity may be accurately predicted by using the recurrence relation established from previous seismicity. Given below is the application of the Guttenberg-Richter recurrence law:

$$\log \lambda_m = a - bm \tag{17}$$

$$\ln \lambda_m = \alpha - \beta m \tag{18}$$

$$\alpha = a \ln 10 \;\; and \; \beta = b \ln 10 \tag{19}$$

where a and b are constants and λ_m is the frequency of earthquakes with magnitudes larger than m.

A probabilistic seismic hazard study considers the likelihood of a fault rupturing as well as the distribution of earthquake magnitudes linked to fault rupture in order to estimate the magnitude of the design ground motion at a location [60]. A framework for recognizing, measuring and integrating uncertainty in earthquake size, location and recurrence rate is provided by a probabilistic seismic hazard analysis [56, 65]. The objective is to offer a more thorough description of the seismic risks at a specific location.

7. Tunnel Lining

According to Yu et al. (2017) [66] and Yu & Chen (2021) [67], the tunnel lining is frequently treated as a subterranean structure vulnerable to ground deformations under two-dimensional plane strain conditions. Tunnel linings are structural systems constructed following excavation that support appurtenances, stop groundwater intrusion, preserve the tunnel aperture, and give ground support, according to Hung et al. (2009) [60]. They also act as a base for the last section of the tunnel that is revealed. They may be utilized for temporary ground support, long-term ground stabilization or a mix of the two. When loads are applied, a tunnel is expected to bend but according to Wang & Munfakh (2001) [68], the deformation depends on how rigid the liner and the ground are in relation to one another. The two ratios used to evaluate relative stiffness are the compressibility ratio (C) and the flexibility ratio (F); the flexibility ratio is the most crucial since it shows how resistant to distortions the lining is [69]. The compressibility ratio is the ratio of the ground's extensional stiffness to the liners. It is the difference between the ground pressure at free-field and the ground pressure needed to induce a unit diametric strain in the liner.

$$Compressibility\ Ratio, C = \frac{E_m(1 - v_l^2)R}{E_1 t(1 + v_m)(1 - 2v_m)} \tag{20}$$

Where: E_m = the medium's elasticity modulus, v_m = The medium's Poisson's ratio, E_l is the tunnel lining's elasticity modulus, v_l is Poisson's ratio of the tunnel lining, R denotes the tunnel lining's radius, t = tunnel lining thickness

The flexibility ratio, or F, is the key metric for assessing the liner's resistance to ground-induced deformation, according to Boldini et al. (2014) [70]. This is the variation in shear stress needed to produce a unit diametric strain between the liner and the free field ground. It is calculated by dividing the liner's stiffness by the ground's flexural stiffness. According to Wang & Munfakh (2001) [68], the flexibility ratio is a measurement of the structure's relative racking stiffness in relation to the surrounding ground.

$$Flexibility\ Ratio, F = \frac{E_m(1-v_l^2)R^3}{6E_l I(1+v_m)} \tag{21}$$

where: E_m = the medium's elasticity modulus, v_m = medium's Poisson's Ratio, E_l = is the tunnel lining's elasticity modulus, v_l = is the tunnel's lining's Poisson's ratio, R = denotes the tunnel lining's radius, t = tunnel lining thickness, I = stands for the tunnel lining's moment of inertia (per unit width) [71].

8. Approach to Seismic Analysis of Tunnels

8.1. Pushover Analysis

Pushover analysis is an innovative approach that is increasingly being studied for both the design of new buildings and the assessment of the seismic performance of existing structures [72 – 74]. It was utilized subsequent to 1970. Over the last 20 years, nonlinear static analysis, sometimes referred to as pushover analysis, has become the accepted technique for design and seismic performance evaluation due to its relative simplicity and integration of post-elastic behavior [75]. Pushover is essentially a structural analysis method based on nonlinear static analysis. This method establishes the analytical framework for a structure. Pushover analysis is a well-liked technique for assessing seismic demand due to its enticing computational features and simple conceptual framework [76, 77]. This particular approach to performance-based design for seismic stress monitors the behavior, strength, and deformation requirements in the earthquake design while progressively increasing the loads in order to evaluate the performance of structures [78, 79]. Numerous incremental nonlinear static experiments are conducted to investigate the lateral deformation and damage pattern of a structure into the inelastic range of behavior under continuous gravity load [80].

According to Liu et al. (2014) [81] and Liu & Liu (2008) [82], the pushover analysis approach is an easy-to-use yet highly successful technique for seismic analysis and structural design. Pushover analysis, according to Rana & Rana (2015) [83], is a useful technique for figuring out the structure's inelastic strength and deformation needs as well as for spotting design errors. By applying incremental lateral loads to any structure, pushover analysis simulates the inertia forces experienced during an earthquake. It is an analysis used to find the capacity curve or force-displacement relationship for a structure or structural element, according to Naqash et al. (2019) [84]. This technique produces a pushover or capacity curve (Figure 5), which is a base shear vs. top displacement curve that shows the nonlinear force-deformation features [85]. This method explicitly accounts for the impacts of nonlinear material responses.

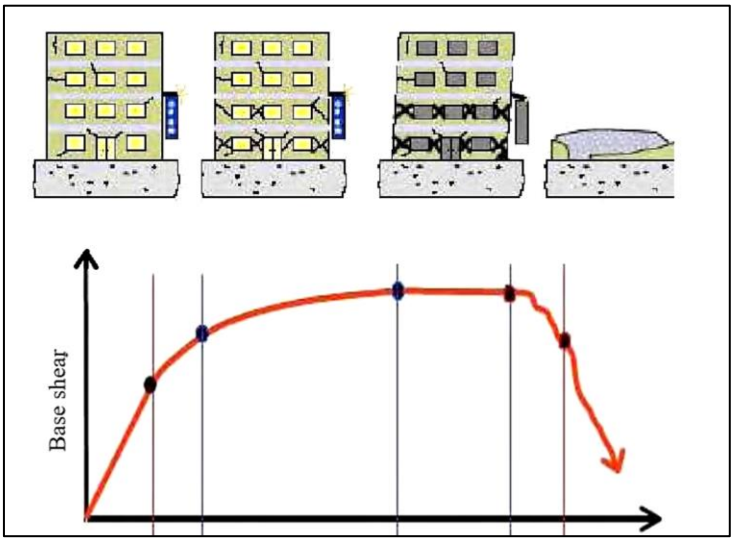

Figure 5. Example of pushover capacity curve [86]

Pushover analysis is primarily predicated on two hypotheses:

- The first few modes of vibration, or the mode shape, control the structure's response; this form holds true for both the elastic and inelastic portions of the structure's response. According to Priyusha et al. (2023) [87], this provides the theoretically flawed basis for converting a dynamic problem into a static one.
- A stable shape vector regulates the deformation of the structures along the height during each load. However, in actuality, the stiffness and form vector of the structure will change after yielding; more study is required to determine if these changes have an impact on the correctness of the results [73].

Pushover analysis can reveal several response characteristics that elastic static or elastic dynamic analysis are unable to provide [88]. They are:

- Determine the forces—such as axial force demands on columns and moment demands on beam-column connections—that are applied to the vulnerable zones.
- Estimates of interstory drifts and their distribution throughout the height.
- Determining the deformation requirements for ductile components
- Locating the weak areas (or probable failure modes) in the structure
- Looking for plan discontinuities or strength elevations that might change the dynamic properties in the inelastic range.
- How a structural system's behavior is impacted as the strength of its constituent parts declines.
- Checking the load path's completeness and sufficiency.

8.2. Incremental Dynamic Analysis

Incremental dynamic analysis, also known as dynamic pushover, has been developed in several forms to assess the performance of buildings under seismic stresses [79]. Incremental dynamic analysis, a widely used method for assessing structural performance under earthquake excitations, is one of the best approaches to look at how various earthquakes impact the behavior of structures [85, 89]. It is possible to directly analyze the variations in structure reaction from record to record by gathering ground-motion data [90, 91]. Incremental dynamic analysis is the cornerstone of seismic risk assessment and seismic performance evaluation [92]. For forecasting seismic behavior under incrementally scaled ground motion, incremental dynamic analysis is a technique [93]. This approach efficiently computes the elastic, yielding, nonlinear elastic, and global dynamic stability responses of the model.

The yielding, elastic, nonlinear elastic and global dynamic instability responses of the model are efficiently computed using this approach. The most crucial step in doing an incremental dynamic analysis is choosing an appropriate intensity measure and engineering demand parameter (Figure 6). This inquiry is represented as a link between the engineering demand parameter (EDP) and the structure's intensity measure (IM). Using the IDA approach, a collection of earthquakes is chosen and applied to the structures [94, 95].

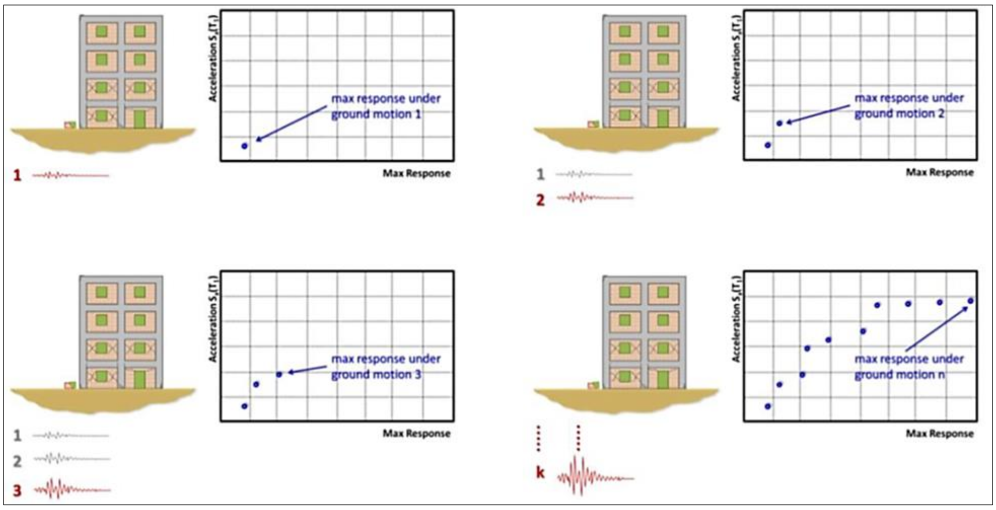

Figure 6. Ground motion scaling in incremental dynamic analysis steps [86]

Soysal & Arici (2014) [96] state that the intensity measure (IM) is a positive scalar that depends on the strength of a ground motion and grows gradually with the scaling factor. IDA attempts to map the inelastic behavior of yielding structures subject to strong ground motions while accounting for the uncertainty of the strong ground motion by using a progressively increasing seismic "intensity measure" (IM) to plot a judicially selected peak structural response quantity, or "engineering demand parameter" (EDP) [97]. According to Vamvatsikos & Cornell (2006) [79], incremental dynamic analysis takes into account how a structural model is affected by one or more ground motion recordings that have been scaled to different degrees of intensity measure. An incremental dynamic analysis must be performed by carefully choosing values for parameters such as the intensity measure (IM) and damage measure (DM) of ground motions [98]. Intensity Measure (IM) – Acceleration of the reaction Peak ground acceleration (PGA) and $S_a(T_i, \xi\%)$ are the most fundamental metrics used to determine intensity. A good IM should, as far as possible, not be dependent on earthquake data, but certain factors, particularly PGA, do. According to the accelerogram's growth or reduction, this number is a function of the initial accelerogram [89]:

$$IM = f\big(\alpha_1(\lambda)\big) \tag{22}$$

Damage Measure (DM) – Positive numerical values of the damage index show that a structure is responding to seismic stresses. In other words, a DM value is a determined number that might reflect a structure's reaction in a dynamics study.

In the elastic zone, an IDA curve is exactly proportional to IM-DM and starts off as a straight line [93]. When the seismic loading reaches a point where the structure yields nonlinearly, the line begins to curve at increasing scaling factors. The reaction of one structure to various earthquake intensities is represented by a single IDA curve. On the same graph, several IDA curves can be displayed, and they each depict how the same structure responds to various seismic events. Different responses from the structure show how important it is to use several IDAs (Figure 7a). In addition, several IDAs may be parametric (Figure 7b) if the model's parameters change in response to the same seismic stress.

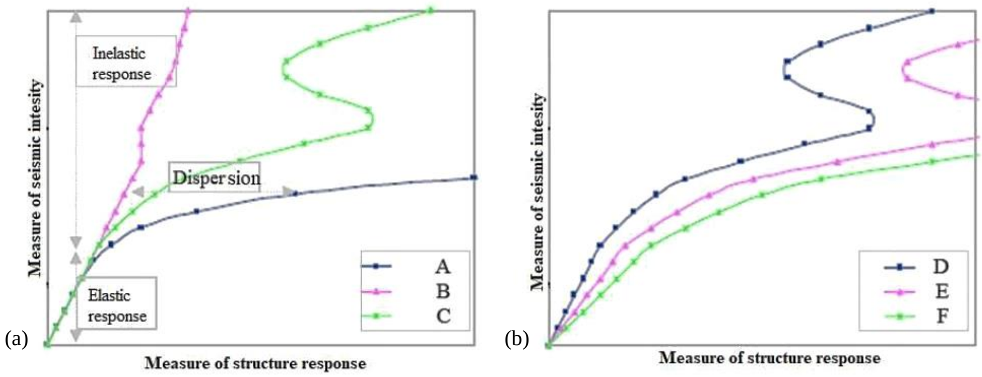

Figure 7. Multiple IDAs: a) seismic, b) parametric [86]

8.3. Response Spectrum Analysis

When it comes to a useful and reliable analytical method for the dynamic calculation of structures subjected to earthquake stimulation, response spectrum analysis (RSA) is one of the most widely used techniques for seismic analysis of structures [99]. The main instrument in engineering seismology is the response spectrum approach, which offers important information for practical applications [100]. A key idea in earthquake engineering is the response spectrum, which offers a workable way to use structural dynamics data in the design of structures. A response spectrum, according to the peak or steady-state response (displacement, velocity or acceleration) of many oscillators with various intrinsic frequencies that are driven by a single base vibration or shock is substantially shown in Rucha et al. (2012) [100]. The highest modal response of a single-support structural system or a structural system with multiple supports that all experience the same stimulus can be determined using response spectrum techniques. Response spectrum analysis is used to describe the maximum physical quantity reaction as a function of the natural period, natural angular frequency, or natural frequency when a structure is subjected to a dynamic load [101]. Response spectrum analysis has two primary approaches: single-point and multi-point techniques.

Single Point Response Spectrum Analysis

A spectrum reacts consistently to each support point in a single point response spectrum analysis [102]. For the purposes of single point response spectrum analysis, the structure is stimulated by a spectrum with known direction and frequency components that operate equally on all support points or on a chosen subset of the master degrees of freedom (DOFs) that are not supported (Figure 8).

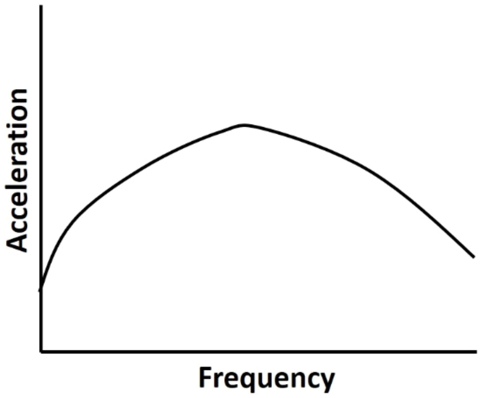

Figure 8. Single point response spectrum analysis

Multi Point Response Spectrum Analysis

Different constrained points may be exposed to various spectra in multi-point response spectrum analysis. The structure may be aroused by various input spectra at various support points or unsupported nodes for multi-point response spectrum analysis. It is possible to have up to 20 distinct input spectra running at once (Figure 9).

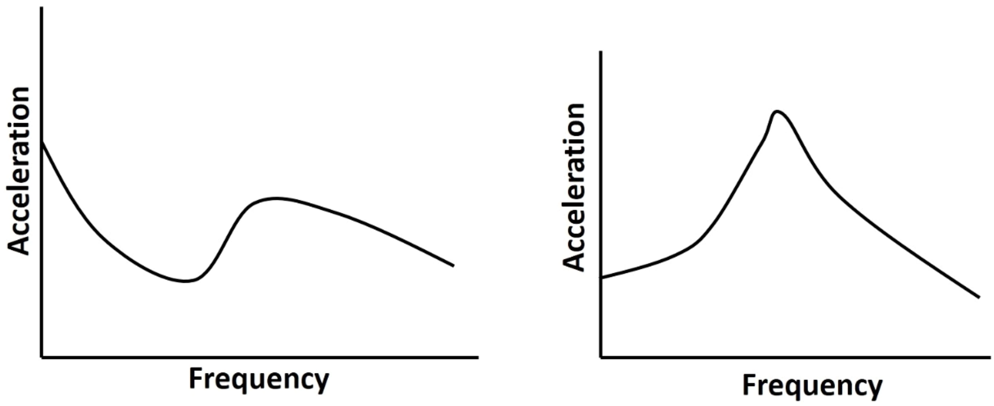

Figure 9. Multi point response spectrum analysis

8.4. Time History Analysis

The methodical examination of a structure's dynamic reaction to a particular stress, which may change over time, is known as time history analysis. Another name for it is dynamic analysis that is nonlinear. According to Barbagallo et al. (2019) [103], nonlinear dynamic analysis is widely thought to be the best method for predicting how structures could respond to earthquakes. According to Wilkinson & Hiley (2006) [104] and Ali et al. (2020) [105], time history analysis is used to ascertain how a structure will react seismically to dynamic pressures during a typical earthquake. It becomes crucial to apply tried-and-true historical methods in order to guarantee protection against seismic activity. The study's goal is to determine the displacement and internal force that occurred throughout the tunnels' construction and loading stages. According to Kumar et al. (2018) [106], the tunnels are vulnerable to seismic shocks while they are in use.

Time history analysis is an exact numerical method that integrates the differential equation of motion directly. The behavior of a structure under data on wind acceleration or past earthquakes is studied using time history analysis. Plotted against time, it represents an amplitude or acceleration. Time history analysis searches for a solution to the dynamic equation when a structure is subjected to dynamic loads [59]. It computes a series of structural reactions (displacements, member forces, etc.) within a predetermined time frame based on the dynamic attributes of the structure under the applied loads [107]. The structural internal forces are therefore calculated for each time step of the time history analysis, which may be utilized to determine the dynamic responses of displacement, velocity, and acceleration [72]. Several ground motion recordings, ideally from genuine earthquake records, are required for conducting an effective time history analysis (Figure 10).

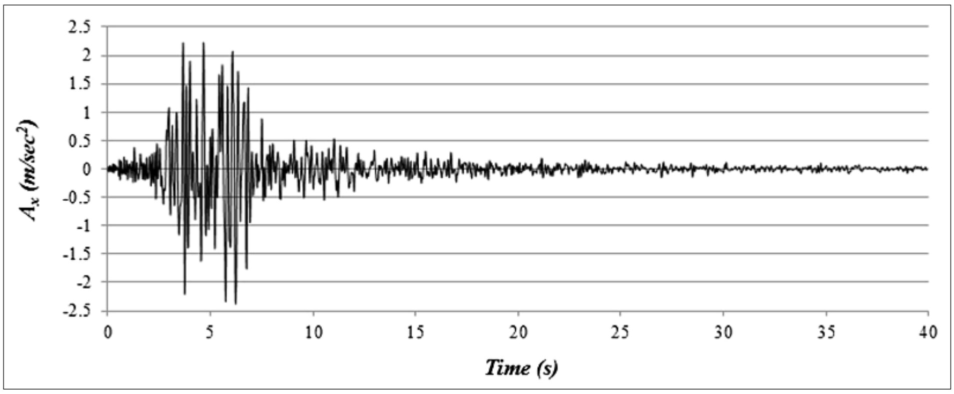

Figure 10. Horizontal acceleration time history of 1991 Uttarkashi earthquake, India [108]

The appropriate modal equation is solved by Equation 23 and the displacement of the structure is calculated by adding the products of each mode form over a time history analysis [109, 110].

$$u(t) = \sum_{i=j}^{m} \emptyset_i q_i(t) \tag{23}$$

With the help of time-history analysis, dynamic structural response to loads may be evaluated linearly or nonlinearly and evaluated in accordance with the chosen time function. The modal or direct integration methods are used to solve the dynamic equilibrium equations that is, $Ku(t) + C\frac{du(t)}{dt} + M\frac{d^2u(t)}{dt^2} = r(t)$ [72]. Non-linear dynamic time history analysis is thought to be a more difficult study situation, requiring many different analysis processes, according to Kumar et al (2018) [106].

9. Analytical Techniques

Analytical techniques for assessing seismic behavior in high ground stress soft rock tunnels are crucial for understanding and predicting tunnel stability under seismic loads. These methods, which vary from empirical models to numerical simulations, are employed to assess how tunnels react to seismic activity [111]. This section explores recent advancements in these techniques, offering new insights, highlighting significant findings and discussing practical applications.

9.1. Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a widely used numerical method for simulating complex physical systems, including tunnels under seismic loading. FEA divides the tunnel and surrounding rock into small elements, allowing for detailed analysis of stress, strain and deformation. Recent advancements include the development of advanced material models that better capture the non-linear behavior of soft rock under seismic loads. El Omari et al. (2021) [112] introduced a material model incorporating both plasticity and damage mechanics to simulate the progressive failure of rock masses. The equation for advanced material model is:

$$\sigma = E \cdot \varepsilon - \eta \cdot \varepsilon^2 \tag{24}$$

where σ is the stress, E is the modulus of elasticity, ε is the strain and η is the damage parameter [112]. By including dynamic loading effects into FEA, Liu et al. (2018) [113] improved the prediction of tunnel response during seismic occurrences. Their approach uses time-dependent boundary conditions to simulate the effects of varying seismic wave frequencies.

9.2. Discrete Element Method (DEM)

The Discrete Element Method (DEM) simulates the behavior of granular and fractured materials by modeling individual particles and their interactions. DEM is particularly useful for understanding the complex interactions within fractured rock masses. Recent research by Hassan & El Shamy (2019) [114] has advanced DEM by incorporating fracture propagation models. These models simulate how fractures evolve under seismic loading, providing insights into the potential failure modes of tunnels in fractured rock. The equation for DEM fracture modeling is:

$$F_{ij} = -k_{ij} \cdot (x_i - x_j) - c_{ij} \cdot (v_i - v_j) + \frac{1}{2} \cdot \beta \cdot (x_i - x_j)^2 \tag{25}$$

where β is the parameter governing fracture propagation [114]. Zhou et al (2024) [115] explored coupling DEM with FEA to model both macro-scale and micro-scale behaviors of rock masses. This approach allows for a comprehensive analysis of tunnel stability, accounting for both large-scale stress distributions and small-scale particle interactions.

9.3. Empirical and Semi-Empirical Models

Empirical and semi-empirical models use observed data and simplified assumptions to estimate tunnel response to seismic loading. These models provide quick assessments but may lack precision compared to numerical simulations. Jain & Rao (2022) [116] developed empirical relationships based on field data to estimate seismic deformation in tunnels. Their model correlates seismic intensity with observed deformation, providing a practical tool for engineers. The equation for empirical deformation estimation is:

$$D = \alpha \cdot S \log_{10}(I) + \beta \tag{26}$$

where D is the deformation, S is the scale factor, I is the seismic intensity and α and β are empirical constants [116].

Recent work by Gaudio et al. (2020) [117] combines empirical data with analytical models to estimate tunnel stability under seismic loading. Their semi-empirical approach incorporates both observed data and theoretical calculations to improve accuracy (Table 5).

Table 5. Comparison of empirical and semi-empirical models for seismic deformation

Model Type	Advantages	Limitations
Empirical	Quick estimation, based on field data	May lack precision for complex cases
Semi-Empirical	Combines empirical data with theory	Requires calibration with field data

9.4. Analytical and Simplified Models

Simplified analytical models provide quick estimates of tunnel stability under seismic loading using simplified assumptions and calculations. Recent research by Xiao et al. (2024) [118] introduced simplified calculation methods that use average ground properties and seismic coefficients to estimate tunnel behavior. These methods are practical for preliminary design and quick assessments. Their work helps bridge the gap between theoretical models and real-world applications.

9.5. Probabilistic and Risk-Based Approaches

Probabilistic approaches account for uncertainty and variability in seismic loading and ground conditions, providing a risk-based assessment of tunnel stability. Man et al. (2023) [119] developed probabilistic models that use Monte Carlo simulations to assess the risk of tunnel failure under varying seismic scenarios. Their approach considers the uncertainty in seismic loads and ground properties. The equation for probabilistic risk assessment is:

$$P(F) = 1 - \exp\left(-\frac{\lambda \cdot t}{\beta}\right) \tag{27}$$

where λ is the failure rate, t is the time, β is the scale parameter and $P(F)$ is the probability of failure [119]. Recent advancements by Lin et al. (2023) [120] integrate probabilistic risk assessments into design practices, allowing engineers to design tunnels with an understanding of the likelihood of various seismic scenarios.

9.6. Empirical-Analytical Hybrid Models

Empirical-analytical hybrid models combine empirical data with analytical approaches to improve prediction accuracy and practical applicability. Recent research by Hu et al. (2020) [121] introduced hybrid models that integrate empirical data with FEA results. Their approach uses empirical correlations to refine FEA simulations, providing more accurate predictions of tunnel behavior. The analytical techniques for assessing seismic behavior in high ground stress soft rock tunnels have evolved significantly, incorporating advanced numerical methods, empirical models, and probabilistic approaches. Recent advancements in Finite Element Analysis, Discrete Element Method, empirical and semi-empirical models, and risk-based approaches provide more accurate and comprehensive tools for predicting tunnel stability and designing effective mitigation strategies. By integrating these techniques, engineers and researchers can better address the challenges posed by seismic loading in soft rock environments.

10. Seismic Behavior Analysis

Seismic analysis of tunnels refers to the simulation and prediction of the structural response of tunnels to ground motion. Numerous studies have considered the effects of seismic hazards on tunnels including ground motion modelling, determination of seismic loads, evaluation of tunnel response and optimization of support systems. Most studies focus on the deterministic approach to seismic analysis which involves the use of data from previous earthquakes and geologic information about the site to forecast the precise ground motion that may be anticipated at a certain location.

Zhang & Liu (2018) [122] and Chen et al. (2019) [123] examined the seismic response of a soft rock tunnel in China that was subjected to high ground stress in one such study. The study examined the behavior of the tunnel under various ground motion scenarios using a computer simulation. The results showed that the reaction was affected by several factors, such as the stiffness of the tunnel, the features of the ground motion, and the interaction between the tunnel and the surrounding soil [124]. Additionally, the investigation showed that the tunnel's seismic behavior differed significantly from that of a tunnel cut out of solid rock. Another work by Trianni et al. (2014) [125] and Wang et al. (2021) [126] looked at the seismic analysis of an Indian tunnel through a soft rock formation with high ground stress. The study estimated the likelihood of different amounts of ground displacement using a probabilistic method to seismic analysis. The findings demonstrated that there was a significant likelihood that the tunnel would sustain seismic damage and that safety improvements were required. Wang et al. (2021) [126] and Sun et al. (2020) [127] examined the seismic behavior of a soft rock tunnel under considerable ground stress in Taiwan in a study. An analysis of the tunnel's behavior under varying ground motion was done in the study using a numerical simulation. The findings indicated that the tunnel needs to have its design altered in order to increase its resistance to seismic damage.

Research was conducted in China by Yao et al. (2021) [128] and Sun et al. (2020) [127] on the seismic response of a soft rock tunnel under extreme ground stress. The study examined the behavior of the tunnel under various ground motion scenarios using a computer simulation. The results showed that the behavior of the tunnel was affected by several factors, such as its stiffness, the features of the ground motion, and the interaction between the tunnel and the surrounding soil. Azadi (2011) [129] assessed the seismic behavior of a soft rock tunnel under high ground stress in Taiwan in a different study. The research employed a probabilistic methodology and seismic data to evaluate the probability of varying degrees of ground movement. The results showed that in order to strengthen the tunnel's resilience to seismic damage, architectural changes are required.

Italy's high ground stress soft rock tunnels' seismic performance was examined in research conducted by Fabozzi et al. (2022) [130]. The research estimated the likelihood of tunnel damage at various degrees of ground motion using a probabilistic method to seismic analysis. The findings indicated that steps needed to be done to enhance the tunnels' safety since they were vulnerable to seismic damage. A numerical model technique was suggested by Wu & Lü (2024) [131] to simulate how a soft rock tunnel would react to seismic ground vibrations. The study indicated that the main barrier of soft ground tunnel seismic analysis was its large deformation behavior. It also demonstrated the importance of considering dynamic degradation and post-liquefaction behavior of the soil in tunnel seismic design.

The impact of in-situ pressures on the seismic response of soft rock tunnels was examined by Wu & Lü (2024) [131]. They came to the conclusion that the elevated ground stress conditions could affect how the tunnel lining reacts to seismic stresses. The study emphasized the significance of taking high ground stress conditions into account while designing tunnel seismically. The impact of various ground motion factors on the seismic response of tunnels were assessed by Gong et al (2021) [132]. They examined a wide range of earthquake event types with various site-specific characteristics and examined how tunnels responded seismically in light of their structural characteristics. The study emphasized the significance of local soil characteristics in tunnel seismic design as well as the necessity of taking into account the frequency and magnitude of ground vibrations. Numerous studies have considered the optimization of support systems to improve the stability of tunnels under seismic loads. Liu et al (2024) [133] optimized the support system for a high ground stress soft rock tunnel under seismic loads. The study examined eight distinct optimization techniques to determine the best support system design, taking into account factors including tunnel lining displacement, stress and deformation. The study proved how crucial it is to take support design into account when designing a tunnel for seismic activity.

11. Case Studies and Examples

Critical infrastructure elements, soft rock tunnels encounter particular difficulties because of their geological setting and seismic stress. Case studies offer important insights into the behavior, difficulties and technical solutions used in the management of these tunnels in different scenarios. By looking at these instances, engineers may draw lessons from the past and use them in their upcoming tunnel projects.

11.1. Mont Blanc Tunnel

The Mont Blanc Tunnel, a critical transportation link between France and Italy under the Alps, has faced significant challenges related to seismic events and other geotechnical risks throughout its history. One of the most notable incidents occurred in 2003, when a seismic event impacted the tunnel, exacerbating existing vulnerabilities following a catastrophic fire in 1999 [134].

A. Incident and Response

1. Background: The Mont Blanc Tunnel spans approximately 11.6 Km and reaches depths of up to 2500 meters beneath the Alps. Its construction through soft rock formations including shale and weakly cemented sandstone, presented inherent challenges related to ground stability and seismic resilience.

2. 1999 Fire: In March 1999, a fire broke out in the tunnel, resulting in tragic fatalities and extensive damage to infrastructure. The subsequent closure and repair efforts underscored the tunnel's vulnerability to both natural and man-made disasters.

3. 2003 Seismic Event: Just four years later, in 2003, the Mont Blanc Tunnel experienced a seismic event that shook the region, highlighting the critical need for enhanced seismic resilience in tunnel infrastructure. The event prompted a reassessment of the tunnel's structural integrity and emergency response protocols [134].

B. Engineering Response

- *Structural Reinforcements:* Following the seismic event, engineers implemented rigorous structural reinforcements to mitigate potential seismic risks. This included:
- *Rock Bolts:* Installation of additional rock bolts to reinforce the tunnel walls and stabilize the surrounding rock mass [26].
- *Shotcrete Application:* Application of shotcrete to enhance the structural integrity of weakened sections and prevent further deterioration under dynamic loading conditions.
- *Seismic Monitoring Systems:* Advanced monitoring systems were integrated to provide real-time data on ground motions and structural responses during seismic events. This enabled proactive measures to be taken to ensure the safety of tunnel users and operational continuity [135].

C. Lessons Learned

The Mont Blanc Tunnel case study emphasizes several critical lessons in tunnel engineering and seismic risk management:

- *Comprehensive Risk Assessment:* Conducting thorough geological surveys and risk assessments is essential for identifying potential hazards and vulnerabilities in tunnel infrastructure.
- *Robust Design and Maintenance:* Implementing robust design principles and maintenance protocols can enhance tunnel resilience against both natural disasters and operational risks.
- *Emergency Preparedness:* Developing and regularly updating emergency response plans is crucial for minimizing risks and ensuring timely interventions during emergencies.

The Mont Blanc Tunnel case study exemplifies the complex challenges and effective engineering responses associated with managing seismic risks in soft rock tunnels. By learning from past incidents and implementing comprehensive risk management strategies, engineers can enhance the resilience and safety of critical tunnel infrastructures in seismically active regions.

11.2. Gotthard Base Tunnel

The 57.1-kilometer-long Gotthard Base Tunnel runs across the Swiss Alps, making it a spectacular technological marvel. It is located in Switzerland. The Gotthard Base Tunnel, the longest railway tunnel in the world, was completed in 2016 and is a noteworthy illustration of earthquake engineering and tunneling methods used in difficult geological circumstances.

A. Geological and Seismic Challenges

- *Geological and Geotechnical Challenges:* Numerous geological and geotechnical difficulties arose during the Gotthard Base Tunnel's construction:
- *Geological Diversity:* The tunnel passes through various geological formations, including gneiss, shale, and limestone, each with distinct mechanical properties and stability considerations [136].
- *High Ground Stresses:* The Alpine region is characterized by high overburden pressures and tectonic activity, leading to complex stress distributions within the rock mass [27].
- *Seismic Design Considerations:* Due to the tunnel's location in a seismically active region, robust seismic design considerations were paramount:
- *Seismic Hazard Assessment:* To describe the possible ground shaking and earthquake scenarios influencing the tunnel alignment, extensive seismic hazard evaluations were carried out.
- *Dynamic reaction Analysis:* To simulate the dynamic reaction of the tunnel structure to seismic waves, sophisticated numerical modelling techniques were used, such as finite element analysis (FEA). These analyses helped predict stress distributions and identify critical zones for reinforcement [135].

B. Engineering Design and Seismic Mitigation Strategies

The construction of the Gotthard Base Tunnel incorporated advanced seismic design principles to ensure safety and operational reliability under seismic conditions. Key engineering strategies included:

- *Rock Mechanics Studies:* Use of rock mass classification methods, such as the Q-system, to measure the quality of the rock mass and direct the construction of tunnel supports [137].
- *Geological Surveys:* Detailed mapping and characterization of geological formations to assess their stability and seismic hazard potential.
- *Tunnel Lining Design:* Flexible and Robust Linings: Designing tunnel linings with flexibility to accommodate ground deformations induced by seismic waves. Reinforced concrete linings with adequate tensile strength and ductility were used to mitigate potential damage during ground shaking [136].
- *Seismic Monitoring and Instrumentation:* Real-Time Monitoring Systems: Installation of sophisticated monitoring systems to continuously assess ground movements and seismic activities within the tunnel and its surroundings. These systems provide early warning alerts to operators, enabling prompt responses to potential seismic threats [135].

C. Lessons Learned and Innovations

The Gotthard Base Tunnel case study highlights several critical lessons and innovations in tunnel engineering under seismic conditions:

- *Integration of Advanced Technologies:* Accurate seismic impact forecasts and well-informed design choices were made possible by the application of empirical techniques such as the Hoek-Brown criteria and numerical modelling tools like finite element analysis (FEA) [26].
- *Holistic Approach to Risk Management:* Combining geological assessments, structural design optimizations and real-time monitoring systems ensured comprehensive risk management and enhanced tunnel safety.
- *Collaboration and Knowledge Sharing:* International collaboration among engineers, geologists and researchers fostered innovation and shared best practices in seismic design and tunnel construction.

The Gotthard Base Tunnel exemplifies the successful application of advanced engineering solutions and seismic design principles to overcome geological challenges and ensure the reliability of critical infrastructure in seismically active regions.

11.3. Lessons Learned

There are many takeaways for the seismic design of soft rock tunnels from these case studies:

- *Integrated Approach:* Combining geological surveys, advanced numerical modelling and robust engineering practices is essential for mitigating seismic risks.

- *Flexibility in Design:* Designing tunnels with flexible linings and adaptive reinforcement strategies enhances resilience against dynamic loading.
- *Monitoring and Early Warning:* Implementing effective monitoring systems allows for timely response to seismic events, minimizing potential damage and ensuring safety.

These two case studies the importance of proactive seismic design and engineering strategies in ensuring the safety and longevity of soft rock tunnels under seismic conditions.

12. Monitoring Systems for Seismic Risk Management in Soft Rock Tunnels

Monitoring systems are essential for managing seismic risks in soft rock tunnels, particularly under high ground stress conditions. These systems provide real-time data on the tunnel's structural integrity, ground movements and seismic activity, enabling timely interventions and adjustments.

12.1. Geotechnical Instrumentation

Geotechnical instrumentation involves the use of various sensors and devices to monitor ground conditions including soil and rock properties, groundwater levels and stress distributions. Recent developments in strain gauges, as discussed by Zhang et al. (2016) [138], include high-resolution sensors that can detect minute changes in strain due to seismic activity. These advanced gauges provide more accurate data on structural responses and allow for better assessment of potential failures. These sensors provide real-time data that can be crucial for assessing the impact of seismic events on groundwater conditions and tunnel stability.

12.2. Seismic Sensors

Seismic sensors detect and measure seismic waves and ground movements. These sensors are critical for assessing the impact of earthquakes and other seismic events on tunnel structures. Recent advancements involve the use of seismic arrays that deploy multiple sensors along the tunnel to create a comprehensive seismic profile. This approach provides a more detailed understanding of seismic wave propagation and its effects on the tunnel. These sensors offer greater flexibility and easier installation, especially in complex tunnel environments.

12.3. Structural Health Monitoring Systems

Structural Health Monitoring (SHM) involves a comprehensive approach to monitoring the overall health and performance of tunnel structures. SHM systems integrate various types of sensors and data analytics to assess structural conditions. Recent innovations include integrated SHM systems that combine multiple sensor types, such as strain gauges, accelerometers, and displacement sensors. Tan et al. (2019) [139] demonstrated that these integrated systems provide a holistic view of tunnel health, improving early detection of potential issues. Wu & Jahanshahi (2018) [140] introduced advanced data fusion techniques that combine data from SHM systems with external factors such as weather conditions and seismic forecasts. This approach provides a more accurate assessment of structural health and helps predict potential failures.

12.4. Strain Monitoring Systems

Strain monitoring systems assess the deformation and stress distribution within tunnel linings and rock masses. They are essential for understanding how seismic events affect tunnel stability. Recent innovations include optical fiber strain sensors that provide continuous, high-resolution strain measurements. Monsberger & Lienhart (2021) [141] developed a distributed fiber-optic sensing system that can measure strain along the entire length of the tunnel lining, offering detailed insights into stress distribution.

12.5. Seismic Monitoring Systems

Seismic monitoring systems detect and measure seismic activity, providing critical information on ground shaking and potential impacts on tunnel stability. Recent advancements include highly sensitive seismic sensors that can detect low-magnitude seismic events with high precision. Li (2021) [142] developed a new seismic sensor array that improves the detection of minor seismic activities, enabling better prediction and preparation for larger events. Ibrahim & Al-Bander (2024) [143] integrated seismic monitoring with hazard analysis models to provide real-time risk assessments and recommendations for emergency response.

12.6. Advanced Data Analytics

Advanced data analytics involves using algorithms and computational methods to analyze data collected from monitoring systems. These techniques help in predicting potential issues and optimizing maintenance strategies. Recent studies by Pu et al. (2020) [144] explored the application of machine learning algorithms to analyze monitoring data. These algorithms can predict tunnel behavior under seismic loading and identify patterns that indicate potential problems. The equation for machine learning prediction is:

$$\hat{y} = f(x;\theta) \tag{28}$$

where $\hat{y}$ is the predicted output, x represents input features and θ denotes model parameters [144]. Tichý et al. (2021) [145] developed predictive maintenance models that use real-time monitoring data to forecast when maintenance should be performed. This approach helps in preventing failures and reducing maintenance costs.

Modern monitoring systems are critical for managing seismic risks in soft rock tunnels. Recent advancements in monitoring systems for soft rock tunnels have significantly enhanced their ability to manage seismic risks and ground stress conditions. Innovations in geotechnical instrumentation, seismic sensors, Structural Health Monitoring (SHM), and advanced data analytics offer new tools and methods for real-time assessment and prediction of tunnel behavior. High-resolution strain gauges, fiber-optic sensors, seismic arrays, wireless technologies, integrated SHM systems and machine learning algorithms contribute to better understanding and management of seismic risks, leading to improved safety and performance of tunnel infrastructure.

13. Mitigation Strategies for Seismic Risks in Soft Rock Tunnels

Mitigation strategies are essential for managing and reducing seismic risks in soft rock tunnels. These strategies encompass structural reinforcements, proactive monitoring, maintenance practices, and a combination of multiple approaches to ensure tunnel stability and safety under seismic loading conditions.

13.1. Structural Reinforcements

Tunnel linings and support systems are better equipped to withstand seismic stresses thanks to structural enhancements. In order to improve strength, flexibility, and general resilience, reinforcements can be made using a variety of materials and methods. Wu & Lü's (2024) [131] concentrated on the application of cutting-edge composite materials for tunnel reinforcing. Fiber-reinforced polymers (FRP), one type of composite reinforcement, has a high strength-to-weight ratio and enhanced durability. Their study showed that FRP reinforcements significantly enhance seismic performance by increasing the energy absorption capacity of tunnel linings. Altalabani et al. (2021) [146] developed new seismic isolation systems using elastomeric bearings and base isolators. These systems absorb and dissipate seismic energy, reducing the forces transmitted to the tunnel structure. Their research demonstrated that seismic isolation can significantly reduce tunnel deformation and damage during an earthquake.

13.2. Reinforcement with High-Performance Materials

Reinforcement with high-performance materials improves the structural integrity of tunnels under seismic conditions. These materials offer enhanced strength, flexibility and durability compared to traditional materials. Recent research focuses on using advanced composite materials for tunnel reinforcement. Composite materials such as fiber-reinforced polymers (FRP), provide high strength-to-weight ratios and excellent resistance to seismic forces. It demonstrated that FRP reinforcement significantly improves the ductility and load-bearing capacity of tunnel linings.

13.3. Seismic Isolation Systems

Seismic isolation systems reduce the impact of seismic forces on tunnel structures by allowing controlled movement between the tunnel and the surrounding ground. Recent innovations in base isolators include elastomeric bearings and sliding bearings that provide enhanced flexibility and energy dissipation. Hu et al. (2020) [121] tested new base isolators with improved performance metrics, showing reduced seismic response and enhanced structural safety. Koleci et al. (2024) [147] developed new isolation materials, such as shape-memory alloys and damping pads, which offer superior performance in high-stress seismic conditions. These materials adapt to seismic forces and provide additional damping.

13.4. Seismic Retrofitting

Seismic retrofitting involves strengthening existing tunnel structures to improve their performance under seismic loads. This approach is particularly relevant for older tunnels that may not meet current seismic standards. Recent studies by Parghi & Alam (2018) [148] explored the use of FRP wrapping for retrofitting tunnel linings. FRP wrapping increases the tensile strength and flexibility of existing structures, improving their seismic resistance. Sun et al. (2024) [149] developed new seismic upgrade techniques, including the addition of external bracing systems and energy-dissipating devices. These upgrades enhance the structural performance and stability of tunnels during seismic events.

13.5. Proactive Monitoring Systems

Proactive monitoring involves using advanced technologies to continuously track the health and stability of tunnels. Early detection of potential issues allows for timely intervention and maintenance. Recent advancements include the integration of artificial intelligence (AI) in monitoring systems. Liu et al. (2023) [150] introduced AI-based predictive analytics that use real-time data from sensors to forecast potential issues and recommend maintenance actions before problems escalate. The equation for predictive maintenance is:

$$P_{maint} = \frac{\sum_{i=1}^{n}(D_i \cdot W_i)}{T_{forecast}} \tag{29}$$

where P_{maint} is the predicted maintenance need, D_i is the data input from sensors, W_i is the weight of each input and $T_{forecast}$ is the forecast time period [150].

Zhao et al. (2023) [151] developed advanced data analytics tools for processing large volumes of monitoring data. Their tools utilize machine learning algorithms to identify patterns and anomalies, providing deeper insights into tunnel behavior under seismic conditions. Zou et al. (2024) [152] introduced real-time data analytics tools that analyze monitoring data to detect early signs of potential issues and recommend maintenance actions before problems escalate.

13.6. Maintenance Practices

Maintenance practices are critical for ensuring the ongoing safety and performance of tunnels. Regular inspections, repairs, and upgrades are essential to address wear and damage, especially after seismic events. Recent research by Zou et al. (2024) [152] introduced smart maintenance scheduling systems that use real-time data and predictive models to optimize maintenance activities. These systems reduce downtime and ensure that maintenance is performed when it is most needed. Tichý et al. (2021) [145] emphasized the use of condition-based maintenance strategies, where maintenance actions are triggered by specific conditions or measurements rather than on a fixed schedule. This approach ensures that maintenance is performed only, when necessary, based on the actual condition of the tunnel.

13.7. Integrated Mitigation Approaches

Integrated mitigation approaches combine various strategies to address seismic risks comprehensively. This includes combining structural reinforcements with proactive monitoring and maintenance practices to create a robust system for managing seismic hazards. Recent work by Liu et al. (2022) [153] developed multi-objective optimization models that balance cost, safety, and performance when implementing mitigation strategies. Their models use advanced optimization techniques to determine the best combination of reinforcements, monitoring systems and maintenance practices. The equation for multi-objective optimization is:

$$Z = \min(\sum_{i=1}^{n}(C_i \cdot X_i)) \tag{30}$$

where Z is the optimization result, C_i is the cost of each component, X_i is the performance index and n is the number of components [153].

Pamukcu (2015) [154] proposed adaptive mitigation strategies that adjust based on real-time data and feedback from monitoring systems. Their approach allows for dynamic adjustments to mitigation measures, enhancing the tunnel's ability to adapt to changing conditions and seismic loads.

Mitigation strategies for seismic risks in soft rock tunnels involve a combination of structural reinforcements, proactive monitoring, and maintenance practices. Recent advancements include the use of advanced composite materials, seismic isolation systems, AI-based predictive analytics and smart maintenance scheduling. Integrating these strategies into a cohesive system enhances tunnel resilience against seismic forces and improves overall safety. By leveraging new technologies and optimizing approaches, engineers can better manage seismic risks and ensure the structural integrity of tunnels in seismic-prone areas.

14. Innovative Approaches and Future Research

As the field of tunnel engineering continues to evolve, addressing the challenges posed by high ground stress and seismic activity demands innovative approaches and cutting-edge research. The traditional methods of tunnel design and reinforcement are increasingly supplemented by advanced technologies, novel materials, and sophisticated analytical techniques. This section explores the forefront of innovation in tunnel engineering, highlighting emerging trends and identifying key areas for future research. By integrating new materials, computational methods, and monitoring technologies, the field aims to enhance tunnel safety, efficiency and resilience.

14.1. The Need for Innovation

The growing complexity of infrastructure projects, coupled with the increasing demands for safety and sustainability, underscores the need for innovative approaches in tunnel engineering. The following factors drive the need for innovation:

- *Increased Urbanization:* As cities expand and populations grow, the demand for new tunnels and infrastructure increases. This requires advanced design methods to ensure that new tunnels can withstand the stresses imposed by urban environments.
- *Extreme Geotechnical Conditions:* Tunnels are often constructed in challenging geotechnical conditions, including high ground stress and variable rock properties. Innovative approaches are needed to address these complexities effectively.
- *Seismic Risk:* With the rising frequency of seismic events due to natural and anthropogenic factors, it is crucial to develop methods that enhance the seismic resilience of tunnel structures.

15. Conclusion

High ground stress soft rock tunnels have complicated seismic behavior including complex interactions between the tunnel lining and rock mass. Deeper understanding of these phenomena has been made possible by developments in seismic wave interaction research and geotechnical characterization. The development of intelligent materials like self-healing concrete, piezoelectric materials, and shape memory alloys opens up new possibilities for enhancing the resilience and performance of tunnels. These materials improve structural integrity by enabling adaptive reactions to changes brought on by stress and earthquakes. More precise and useful insights into seismic hazards are offered by recent advancements in performance-based design, probabilistic seismic hazard assessment, and ground motion prediction models. These models leverage machine learning, real-time data integration, and nonlinear site response analyses to improve risk assessment and design practices. Real-world examples such as the Longtan Hydropower Project and the Tokamak Complex (ITER), illustrate the practical application of these advanced methodologies and materials. These case studies highlight the effectiveness of innovative approaches in addressing the challenges posed by high ground stress and seismic activities. The integration of real-time monitoring systems, numerical modeling, and structural reinforcement strategies has significantly improved the ability to assess and mitigate seismic risks. Techniques such as advanced seismic sensors, adaptive reinforcement systems, and self-healing materials contribute to more robust and resilient tunnel structures.

Addressing the challenges of seismic behavior on high ground stress soft rock tunnels requires a multifaceted approach that combines advanced materials, innovative technologies, and improved modeling techniques. The advancements discussed in this review highlight the significant progress made in enhancing tunnel safety and resilience. The area of tunnel engineering may better manage the difficulties of seismic and geotechnical situations by continuing to investigate new approaches and technology, which will ultimately result in safer and more dependable infrastructure.

16. Declarations

16.1. Data Availability Statement

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16.3. Conflicts of Interest

The author declares no conflict of interest.

17. References

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