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Enhancing Seismic Damage Assessment in Rock Tunnels: A Comprehensive Classification Approach

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Abstract

Rock tunnels sustained damages from earthquakes like those in Duzce, Chi-Chi, Wenchuan, etc. The damage degree and its classification are crucial factors in assessing the Seismic Vulnerability of Rock Tunnels (SVRT) from earthquakes. Numerous researchers have focused on classifying post-earthquake damage classifications in tunnels. However, these post-seismic damage classifications of tunnels were periodically modified after seismic events based on the amount of damage observed in the tunnels. Extensive data from various seismic events is required to establish a uniform classification. This study provides a Seismic Damage Classification of Tunnels (SDCT) framework and methodology to assess damage before an earthquake. This classification is developed by creating the largest database incorporating data from 235 damaged tunnel sites from 26 different earthquakes worldwide. The damage data and descriptions are derived from actual tunnel sites that have been damaged by earthquakes. This paper provides an overview of three things. Firstly, the SDCT framework is provided. Secondly, by using the SDCT framework, a simplistic method for assessing SVRT before an earthquake is detailed. Lastly, the application of this method in the field through developed software is given. The simplistic method will provide global engineers with insights into the importance of seismic damages and influence parameters of tunnels residing in seismic zones. The simplistic method, which is utilized for developing software, offers insights into predicting probable seismic damage to the tunnel before an earthquake. With this software, rock and tunnel engineers can conduct SVRT analyses, producing comprehensive reports and graphs prior to an earthquake, thereby enabling rapid and preliminary seismic assessments.

Keywords

Seismic Damages, Rock Tunnels, Earthquakes, Damage Classification.

1 Introduction

Tunnels play a vital role in infrastructure development, supporting the growth of transportation, energy, and other industries. While rock tunnels were considered resistant to earthquakes, recent damage cases have challenged this assumption (Wang et al. 2001, Shen et al. 2014). Numerous instances of severe seismic damage and even the collapse of rock tunnels were reported in the literature (Dowding and Rozen 1978; Wang et al. 2001). Various types of seismic damage experienced by rock tunnels include shear failure in tunnel linings, slope failures in mountain tunnels, lining spalling, portal damage, invert damage, lining cracks, and groundwater leakage (Reddy and Singh, 2024a). A few of these damages are shown in Fig. 1 (a-d). Various studies (Dowding and Rozen 1978; Wang et al. 2001; Wang and Zhang 2013; Shen et al. 2014; Yu et al. 2016) classified seismic damage to tunnels based on investigations conducted after earthquakes. The existing damage classifications are based on post-seismic damages. Seismic damage classification is a major component in understanding the vulnerability of rock tunnels from earthquakes. For the first time, a simple approach to assess the Seismic Vulnerability of Rock Tunnels (SVRT) before an earthquake is provided by Reddy and Singh (2024a) using the Seismic Damage Classification of Tunnels (SDCT) framework. This paper presents the methodology of Reddy and Singh (2024a) for assessing seismic damage in rock tunnels and its practical application in the field through a developed software, designed for use in India and adjacent countries.

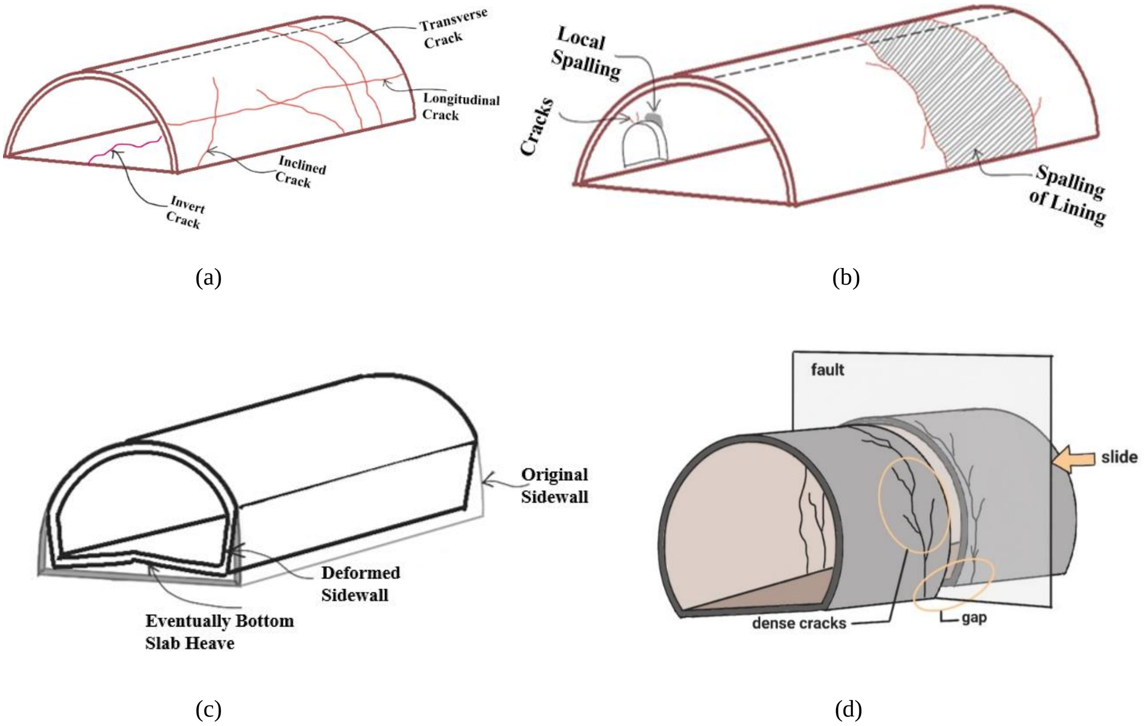

Fig. 1 Seismic damages of tunnel (a) Lining cracks (b) Lining Spalling (c) Lining Deformation (d) Lining Dislocation (after Reddy and Singh, 2024a).

2 Seismic Damage Assessment of Rock Tunnels by Reddy and Singh's (2024a) Approach

The recent study by Reddy and Singh (2024a) provides the SDCT framework. Building on the SDCT framework, the authors developed a simplistic approach to assess the SVRT before an earthquake occurs. This section has two sub-sections. The first one provides an overview of the SDCT framework, followed by an overview of a simplistic method for assessing SVRT using the SDCT framework.

2.1 Overview of SDCT Framework

Reddy and Singh's (2024a) approach was derived from the world's largest database of seismic damage to rock tunnels. The global database comprised 236 rock tunnel sites damaged by 26 different earthquakes (Reddy and Singh, 2024a). The SDCT framework is based on seismic damage to tunnel lining, portal, and invert. A total of 18 damage categories (10 for lining, 5 for portal, and 3 for invert) were identified from actual damage cases in the database. The SDCT is shown in Fig. 2. The SDCT categorizes seismic damage to rock tunnels into seven classes: Extremely High (EH), Very High (VH), High (H), Moderate (M), Low (L), Very Low (VL), and Extremely Low (EL) (Reddy and Singh, 2024a). All the damage categories are assigned with each damage class and are defined by damage description, amount of damage, and Potential Secondary Damages (PSD), as detailed in Reddy and Singh (2024a). Further, a thorough analysis is done to identify the critical parameters from the database. The identified parameters include Moment Magnitude (Mw), Source-Site Distance (SSD), Peak Ground Acceleration (PGA), Rock Mass Rating (RMR), Overburden Depth (OD), order of criticality of tunnel shapes, and lining types (Reddy and Singh, 2024a). A comprehensive set of critical parameters and probable damage categories in each damage class were identified. This led to the development of criteria for future applicability, outlining the critical combinations of parameters for each damage class to predict seismic damage as detailed in Reddy and Singh (2024a). Employing quantitative RMR, OD, PGA values (dependent on Mw and SSD), and qualitative descriptions of shape criticality and lining types, the combinations are established for each damage class. This means that if the proposed parameter ranges for a given damage class are met, the probable damages to the tunnel's lining, portal, and invert can be predicted within the proposed SDCT framework. For detailed tables, please refer to Reddy and Singh (2024a).

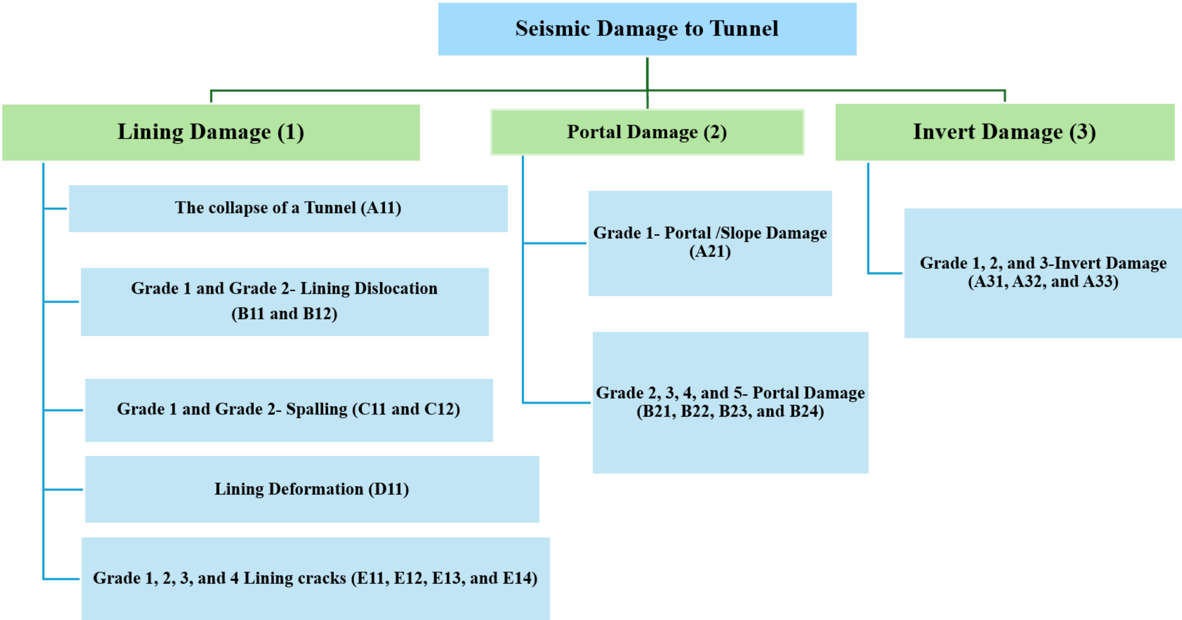

Fig. 2 The SDCT framework and its 18 damage categories (after Reddy and Singh, 2024a).

2.2 Simplistic Approach to Assess the SVRT Before an Earthquake

The SDCT framework is further utilized in developing a simplistic approach to assessing the SVRT before an earthquake (Reddy and Singh, 2024a). Fig. 3 shows the simplistic method using the SDCT framework. Seismic sources within a 250 km radius of the tunnel site should be identified and mapped using Google Earth Pro or QGIS (Reddy and Singh, 2024a). To determine the Shortest Source-to-Site Distance (SSD), consider the tunnel's length: for tunnels ≤ 2 km, measure SSD from either of the tunnel portals, whereas for tunnels > 2 km, measure SSD from the most critical section of rock mass in the tunnel (Reddy and Singh, 2024a).

The next step is to obtain the PGA using a region-based attenuation relationship and obtain other critical parameters of the tunnel site as shown in Fig. 3. After obtaining all of them, they are combined to obtain damage class, which would lead to probable seismic damages of the tunnel site (Reddy and Singh, 2024a). In this way, the proposed SDCT framework and simplistic method given in Fig. 3. will provide SVRT before an earthquake. For comprehensive tables on the critical combination of parameters for each damage class, please refer to Reddy and Singh (2024a). This method provides a straightforward approach to assessing tunnel damage, eliminating the need for intricate calculations or numerical modelling (Reddy and Singh, 2024a). By applying the current methodology to rock tunnels, tunnel planners and engineers can gain valuable insights, enabling them to make informed decisions about the necessity of further site-specific seismic investigations (Reddy and Singh, 2024a).

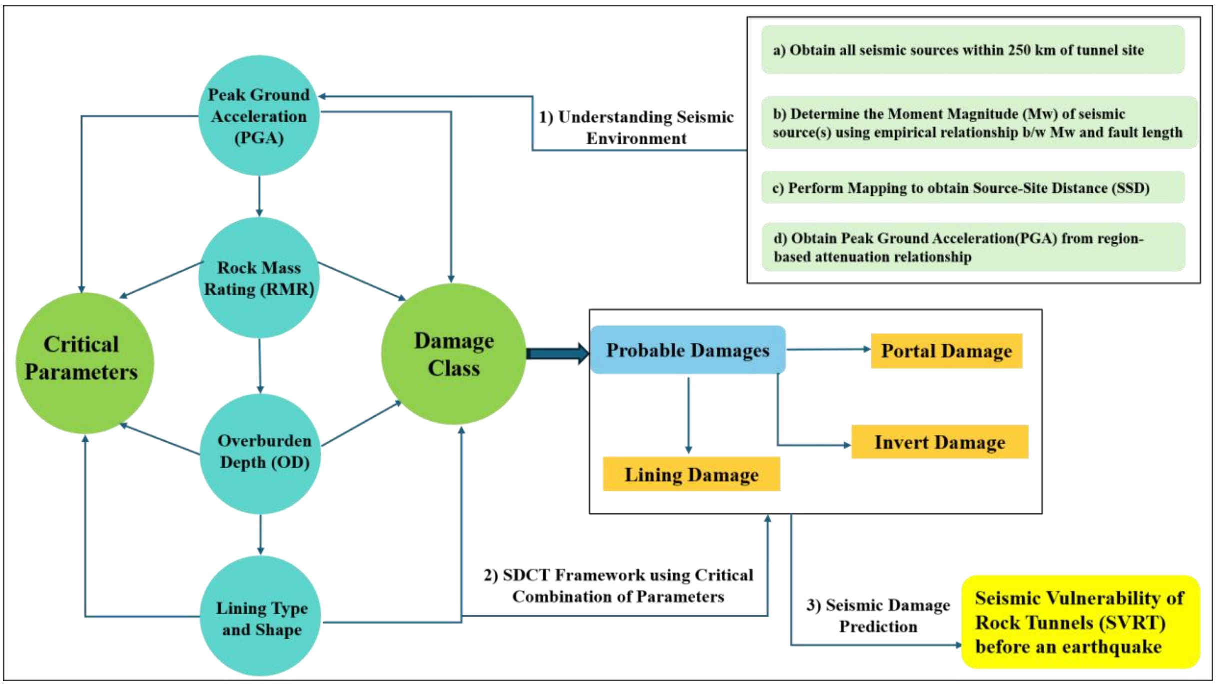

Fig. 3 Methodology for seismic damage assessment of rock tunnel before an earthquake using SDCT framework (after Reddy and Singh, 2024a)

3 Application of Simplistic Method in Field using a Software

The simplistic method given by Reddy and Singh (2024a) for assessing seismic damage of rock tunnels before an earthquake is discussed above and is shown in Fig. 3. The important step in this approach is to identify the seismic sources within 250 km of the tunnel site. Although the method is simple, the whole process is time-intensive and requires precision from start to end of this method (Reddy and Singh, 2024b). The reasons are:

- Seismic sources within 250 km of tunnel site are to be obtained from various databases and literature.
- They are to be organized and arranged systematically and are to be mapped in Google Earth Pro or QGIS to obtain SSD for finding PGA.
- After PGA, the tunnel site parameters are to be obtained.
- Once all critical parameters are collected, the engineer should analyse critical parameter combinations to obtain the damage class from all the faults within 250 km. For ex: if ten faults are within 250 km, the damage class from all the ten faults is to be obtained.
- The engineer must be precise in obtaining the damage class for each fault.
- After obtaining the damage class for all faults within 250 km, they should be organized clearly to obtain probable damages to a tunnel.

Considering the above reasons, software has been developed to simplify and implement the proposed methodology in the field (Reddy and Singh, 2024b). This software effectively addresses the limitations of the manual process, which can be time-consuming and provides precision throughout (Reddy and Singh, 2024b). The software is a Python-powered Graphical User Interface (GUI) tool specifically designed for India and neighbouring countries for performing preliminary seismic risk assessments of rock tunnels (Reddy and Singh, 2024b). A comprehensive database of 4,602 seismic sources was created by collecting and mapping faults across India and neighbouring countries using QGIS, laying the foundation for the development of this tool (Reddy and Singh, 2024b). The mapping of these faults is shown in Fig. 4.

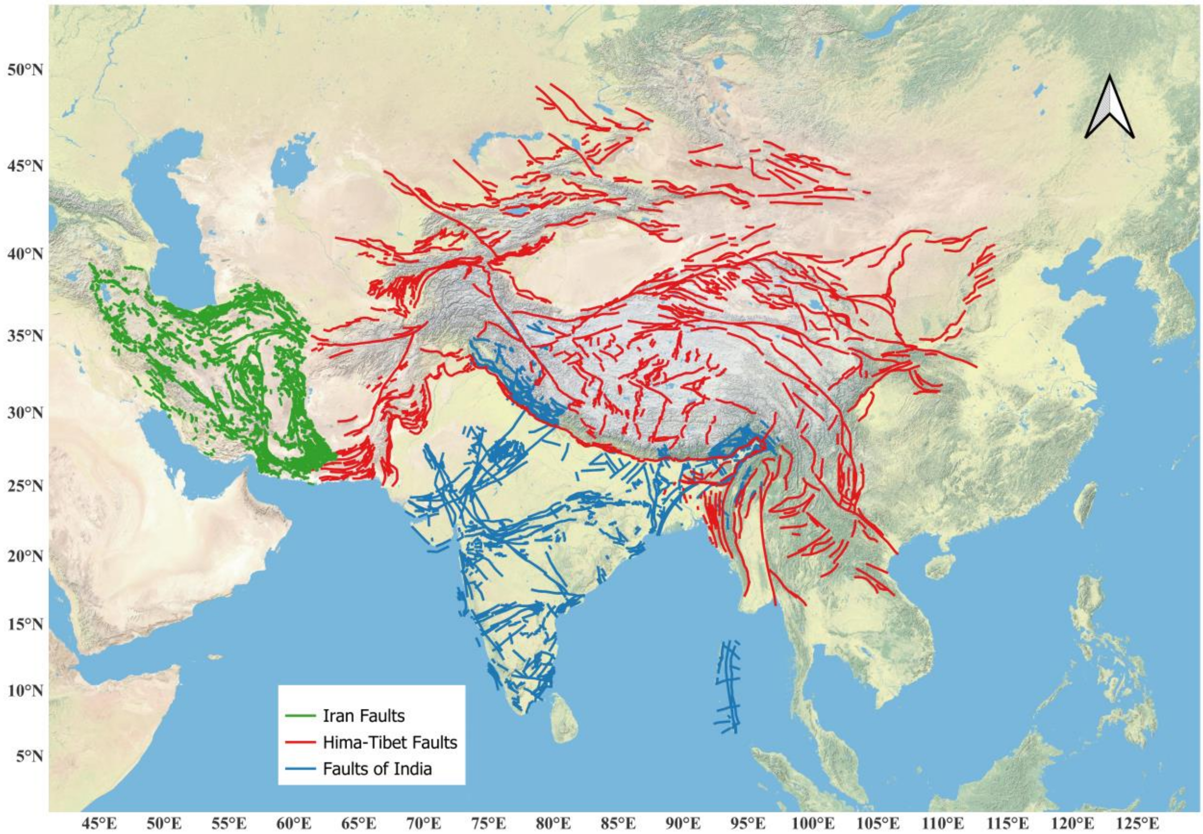

Fig. 4 Seismotectonic map of India and neighbouring countries for 4602 faults created with QGIS 3.32.2. (after Reddy and Singh, 2024b)

The Python code retrieves seismic sources within a 250 km radius of the tunnel site and calculates the PGA from each source using region-based empirical attenuation relationships (Reddy and Singh, 2024b). This software assesses the SVRT by integrating input parameters such as latitude of site, longitude of site, RMR, OD (in m), lining type, and tunnel shape (Reddy and Singh, 2024b). Leveraging PGA values from seismic sources within a 250 km radius, the software critically combines all these parameter inputs to predict the damage class and potential seismic damages before an earthquake for any tunnel site within the study region (Reddy and Singh, 2024b). The software generates comprehensive reports in .txt format, along with graphical representations illustrating the distribution of total faults in each damage class specific to the user's location (Reddy and Singh, 2024b). The whole process of the software's input to output is shown in Fig. 5.

The outlook of GUI, the working methodology of the software, and the software's output are shown in Fig. 5. The software features a 'Tool Info' button, conveniently located on the right, which provides a brief overview of the tool's functionality and purpose (Reddy and Singh, 2024b). In addition to assessing the SVRT, this GUI tool also provides a secondary function for performing Deterministic Seismic Hazard Analysis (DSHA) for sites located within a 250 km radius (Reddy and Singh, 2024b). The user has the feasibility to select either SVRT or DSHA. If one option is selected, the other analysis will be automatically disabled. Although the primary focus of the software is on the SVRT, this GUI tool also offers a supplementary function for conducting DSHA for sites within a 250 km radius (Reddy and Singh, 2024b). To demonstrate the software's application, an example is shown for a specific location. An example location with designated latitude, longitude, and critical parameters was inputted into the software, and the resulting output is illustrated in Fig. 5. Thus, utilizing this software, rock and tunnel engineers can easily perform SVRT and generate reports and graphs before an earthquake, facilitating quick and preliminary seismic investigations (Reddy and Singh, 2024b). The technical details of the construction of the fault database and the methodology utilized for developing software by Python programming are not provided here. This work is based on the research conducted by Reddy and Singh (2024b). For a more comprehensive understanding, readers may refer to their forthcoming journal article.

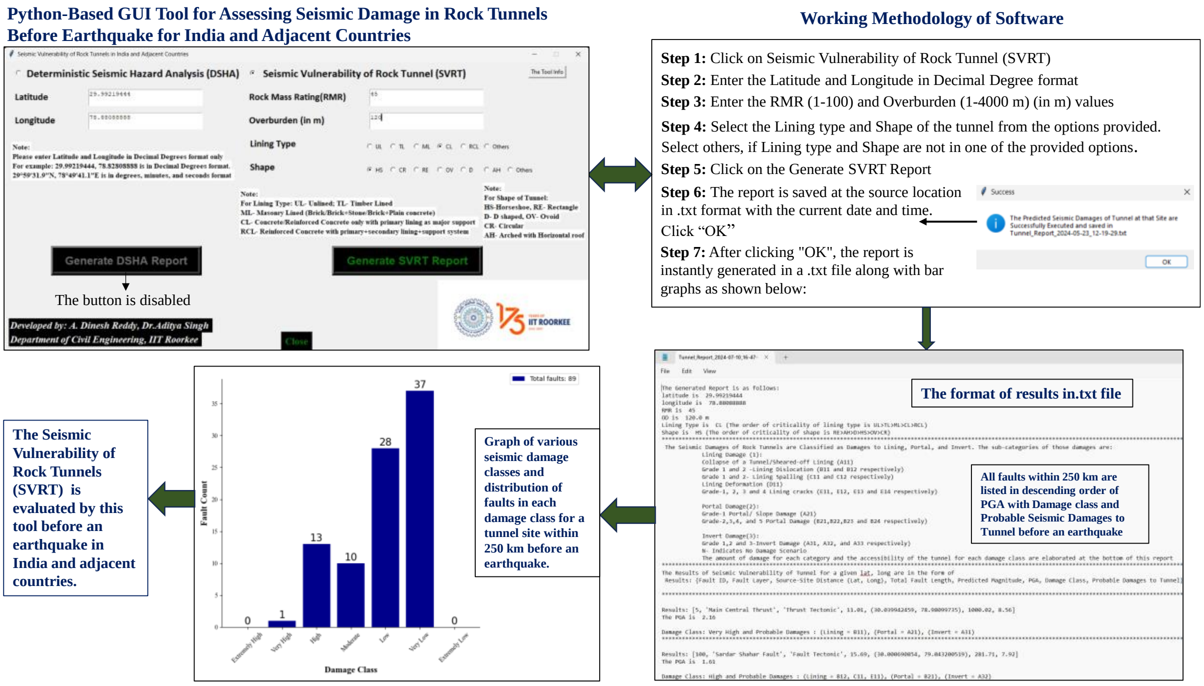

Fig. 5 Methodology and functionality of the software for performing SVRT (after Reddy and Singh, 2024b)

4 Conclusions

This study presents a straightforward method for predicting and assessing seismic damage to rock tunnels prior to an earthquake, building upon the research of Reddy and Singh (2024a). This method is further simplified through the development of user-friendly software, specifically designed for India and neighbouring countries. The rapid increase in the construction of tunnels in seismically active regions of India leads to the development of this tool for conducting preliminary seismic investigations of rock tunnel sites. The reports generated by this tool provide a valuable head start in identifying the need for seismic-related investigations for tunnel projects. Through this software, if the report reveals a significant seismic source along the planned route, designers or engineers can consider re-routing to minimize potential seismic damage. Conversely, if the software predicts moderate to very low damage classes, targeted mitigation measures can be implemented to safeguard the tunnel before an earthquake strikes. The current application of the proposed software is limited to India and neighbouring countries. However, future expansions can include the incorporation of additional seismic sources from other countries, enhancing the software's global applicability. For a detailed evaluation of tunnel seismic response, site-specific numerical analysis is recommended. However, the software presented here offers a preliminary assessment to identify the need for such in-depth seismic investigations. This study is part of the work by Reddy and Singh (2024a, 2024b). For detailed insights, the authors recommend referring to their published journal article (Reddy and Singh, 2024a) and the other forthcoming journal article (Reddy and Singh, 2024b).

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