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Research on the educational management model for the interplay of structural damage in buildings and tunnels based on numerical solutions

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Abstract. The effective management of damage in tunnels is crucial for ensuring their safety, longevity, and operational efficiency. In this paper, we propose an educational management model tailored specifically for addressing damage in tunnels, utilizing numerical solution techniques. By leveraging advanced computational methods, we aim to develop a comprehensive understanding of the factors contributing to tunnel damage and to establish proactive measures for mitigation and repair. The proposed model integrates principles of tunnel engineering, structural mechanics, and numerical analysis to facilitate a systematic approach to damage assessment, diagnosis, and management. Through the application of numerical solution techniques, such as finite element analysis, we demonstrate the efficacy of the proposed model in simulating various damage scenarios and predicting their impact on tunnel performance. Additionally, the educational component of the model provides valuable insights and training opportunities for tunnel management personnel, empowering them to make informed decisions and implement effective strategies for ensuring the structural integrity and safety of tunnel infrastructure. Overall, the proposed educational management model represents a significant advancement in tunnel management practices, offering a proactive and knowledge-driven approach to addressing damage and enhancing the resilience of tunnel systems.

Keywords: educational management; numerical method; structural damage; tunnel

1. Introduction

In recent years, the field of educational management has witnessed an increasing focus on developing effective strategies for addressing the interplay of structural damage in buildings and tunnels. With the growing complexity of modern infrastructure and the ever-present threat of natural disasters and human-induced hazards, there is a pressing need to enhance our understanding of structural behavior and resilience. This necessitates the integration of advanced numerical solutions into educational management models to mitigate risks, ensure safety, and optimize resource allocation.

This paper embarks on a comprehensive exploration of the educational management model for addressing the interplay of structural damage in buildings and tunnels. By leveraging numerical solutions and innovative methodologies, we aim to elucidate key principles, methodologies, and best practices for enhancing structural resilience, minimizing risks, and optimizing educational resources.

Background and Context: The built environment encompasses a vast array of structures, including buildings, bridges, tunnels, and other infrastructure. Ensuring the safety and resilience of these structures is paramount, as they serve as critical lifelines for communities, economies, and societies at large. However, the structural integrity of these assets is constantly challenged by various factors, ranging from natural disasters such as earthquakes, floods, and hurricanes to human-induced hazards like terrorist attacks and accidents.

Educational institutions play a pivotal role in equipping future generations of engineers, architects, and decision-makers with the knowledge, skills, and tools necessary to address these challenges effectively. By integrating practical insights and real-world applications into educational curricula, students can develop a deep understanding of structural behavior, risk assessment, and resilience planning.

Challenges and Opportunities: Despite the growing recognition of the importance of structural resilience, educational institutions face numerous challenges in developing comprehensive educational management models. These challenges include the rapid advancement of technology, evolving regulatory frameworks, limited resources, and the need for interdisciplinary collaboration. Moreover, traditional teaching methods often fail to provide students with hands-on experience and practical exposure to real-world scenarios.

However, these challenges also present opportunities for

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innovation and collaboration. By leveraging advanced numerical solutions, such as finite element analysis, computational fluid dynamics, and structural optimization techniques, educational institutions can bridge the gap between theory and practice. Additionally, interdisciplinary partnerships with industry stakeholders, government agencies, and research institutions can enrich educational programs and foster a culture of continuous learning and improvement.

Objectives and Scope: The primary objective of this paper is to develop a comprehensive educational management model for addressing the interplay of structural damage in buildings and tunnels. To achieve this objective, we will:

Review existing literature and best practices in educational management and structural engineering.

Identify key challenges and opportunities in addressing structural damage in buildings and tunnels.

Explore the application of advanced numerical solutions in educational settings.

Propose a framework for integrating numerical solutions into educational curricula.

Discuss case studies and practical examples to illustrate the effectiveness of the proposed model.

Significance and Contribution: This research holds significant implications for both academia and industry. By developing an educational management model that integrates advanced numerical solutions, educational institutions can enhance the quality and relevance of their programs, better prepare students for real-world challenges, and contribute to the advancement of structural engineering practice. Additionally, industry stakeholders stand to benefit from a pipeline of skilled professionals equipped with the knowledge and expertise to address complex structural issues and enhance infrastructure resilience.

In the realm of mathematical modeling within structural engineering, researchers have delved into a plethora of studies aimed at understanding the dynamic behavior and responses of various structural configurations under diverse loading conditions. This introduction highlights several seminal contributions in this domain, showcasing the breadth and depth of research endeavors aimed at enhancing our comprehension of structural dynamics and resilience.

Kumar *et al.* (2013) embarked on an investigation into the vibrational characteristics of cylindrical sandwich shells, employing the Zigzag theory as a foundational framework. Their study shed light on the intricate dynamics of sandwich structures, offering valuable insights into their vibrational behavior. Expanding on this line of inquiry, Seo *et al.* (2015) delved into the vibration response of cylindrical shells containing internal fluid. Leveraging finite element solution procedures, their research provided a comprehensive understanding of the dynamic interactions between fluid and shell structures, with implications for a wide range of engineering applications. In a subsequent study, Katariya and Panda (2019) delved into the frequency, deflection, and transient responses of sandwich layered shell structures subjected to varying mechanical loads. Their investigation contributed to the burgeoning field of structural dynamics, offering novel methodologies for analyzing and optimizing the performance of complex structural systems. Meanwhile, Keshtegar *et al.* (2020) ventured into the realm of dynamic stability analysis, focusing on sandwich nanocomposite truncated conical shells. Employing the differential cubature method, their research elucidated the stability characteristics of these intricate structures, with implications for aerospace and automotive applications. Tran *et al*. (2020) directed their attention to the numerical free-vibration response of functionally graded stiffened cylindrical shells embedded in Winkler–Pasternak foundations. Their study provided valuable insights into the vibrational behavior of composite structures, informing the design and optimization of resilient engineering solutions.

The exploration of structural responses under extreme loading conditions continued with Skob *et al.* (2020), who delved into the numerical analysis of damage probability in mine tunnels subjected to explosions of hydrogen-air mixtures. Their research offered critical insights into risk assessment and mitigation strategies for underground infrastructure. Similarly, Tiwari *et al*. (2020) presented a groundbreaking study on 3D nonlinear finite element responses in curved structures under internal blast loading. Their research addressed the complex dynamics of blast-induced deformations, with implications for structural safety and resilience in hazardous environments. Continuing this trajectory, Zaid and Rehan Sadique (2020) undertook a dynamic analysis of rock tunnels subjected to blast loads, utilizing finite element methodologies. Their investigation contributed to the understanding of blast-induced structural responses, informing the design and reinforcement of underground tunnels in military and civilian contexts. Meanwhile, Wu *et al.* (2020) focused on the mechanical response of circular tunnels with double primary linings in squeezing grounds. Their study addressed the challenges posed by ground instability, offering innovative solutions for enhancing tunnel resilience and longevity. Lastly, Hong *et al.* (2020) delved into the interactive effects between existing structures and surrounding ground during the excavation of divergence tunnels. Their research provided critical insights into the complex interactions between infrastructure and geotechnical conditions, guiding excavation practices and risk management strategies. Collectively, these studies exemplify the rich tapestry of research endeavors within the realm of structural dynamics and resilience, underscoring the interdisciplinary nature of modern engineering and the relentless pursuit of innovative solutions to address the evolving challenges of infrastructure design and management.

In conclusion, this paper sets out to develop an innovative educational management model for addressing the interplay of structural damage in buildings and tunnels. By leveraging advanced numerical solutions and interdisciplinary collaboration, we aim to empower educational institutions to equip future generations with the skills, knowledge, and mindset necessary to tackle the challenges of the built environment effectively. Through this endeavor, we seek to contribute to the advancement of structural engineering practice and the promotion of resilient, sustainable infrastructure for generations to come.

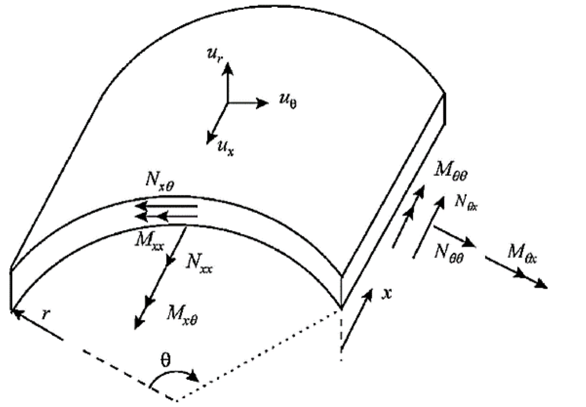

Fig. 1 A schematic figure for the force and moments as well as deflections in three directions the shell

2. Educational management and modeling

In this paper, classical theory is used. Classical shell theory, which is a fundamental part of structural mechanics, is built upon several hypotheses that simplify the analysis of structures like cylindrical and spherical shells. These hypotheses form the basis of the theory and allow engineers to make approximations that significantly simplify the mathematical treatment of shell structures. Here are the key hypotheses underlying classical shell theory:

- **Kirchhoff-Love Hypothesis**: This hypothesis assumes that the normal to the middle surface of the shell remains normal to the deformed middle surface after deformation. This simplifies the analysis by allowing for the use of 2D theories rather than full 3D treatments.
- **Thinness Hypothesis**: Classical shell theory assumes that the thickness of the shell is much smaller compared to the other dimensions of the shell, such as its radius or diameter. This assumption allows for the reduction of the 3D problem to a 2D one, thus simplifying the analysis.
- **Constant Curvature Hypothesis**: Classical shell theory often assumes that the middle surface of the shell has a constant curvature.
- **Material Homogeneity and Isotropy**: The material of the shell is assumed to be homogeneous (uniform throughout) and isotropic (having the same properties in all directions). This simplifies the analysis by allowing the use of well-established material models and simplifies the formulation of constitutive equations.

By making these simplifying assumptions, classical shell theory provides a powerful framework for analyzing the behavior of structures, allowing engineers to predict their response to various loading conditions and design efficient and reliable structures. Displacement field can be expressed as below based on the classic theory (Reddy 2004).

$$u_1(x,\theta,z,t)=u(x,\theta,t)-z\frac{\partial w(x,\theta,t)}{\partial x}, \tag{1}$$

$$u_2(x,\theta,z,t)=v(x,\theta,t)-\frac{z}{R}\frac{\partial w(x,\theta,t)}{\partial \theta}, \tag{2}$$

$$u_3(x,\theta,z,t)=w(x,\theta,t), \tag{3}$$

The potential energy of the structure (U) is as the following

$$\begin{aligned}U=\int_A\Bigg(&N_x\left(\frac{\partial u}{\partial x}+0.5\left(\frac{\partial w}{\partial x}\right)^2\right)-M_x\frac{\partial^2 w}{\partial x^2}+N_\theta\left(\frac{\partial v}{R\partial\theta}+\frac{w}{R}+0.5\left(\frac{\partial w}{R\partial\theta}\right)^2\right)\\&-M_\theta\frac{\partial^2 w}{R^2\partial\theta^2}+N_{x\theta}\left(\frac{\partial u}{R\partial\theta}+\frac{\partial v}{\partial x}+\frac{\partial w}{R\partial\theta}\frac{\partial w}{\partial x}\right)-2M_{x\theta}\frac{\partial^2 w}{R\partial\theta\partial x}\Bigg)dA\end{aligned} \tag{4}$$

where the force and moments as well as deflections in three directions are shown in Fig. 1.

$$\begin{Bmatrix}N_x\\N_\theta\\N_{x\theta}\end{Bmatrix}=\int_{-\frac{h}{2}}^{\frac{h}{2}}\begin{Bmatrix}\sigma_x\\\sigma_\theta\\\tau_{x\theta}\end{Bmatrix}dz, \tag{5}$$

$$\begin{Bmatrix}M_x\\M_\theta\\M_{x\theta}\end{Bmatrix}=\int_{-\frac{h}{2}}^{\frac{h}{2}}\begin{Bmatrix}\sigma_x\\\sigma_\theta\\\tau_{x\theta}\end{Bmatrix}zdz, \tag{6}$$

Kinetic energy of the tunnel (K) is

$$K=\int\left(\frac{\rho}{2}\left(\frac{h^3}{12}\left((\frac{\partial^2 u}{\partial t\partial x})^2+(\frac{\partial^2 w}{\partial t\partial\theta})^2\right)\right)+h\left((\frac{\partial u}{\partial t})^2+(\frac{\partial v}{\partial t})^2+(\frac{\partial w}{\partial t})^2\right)\right)dA. \tag{7}$$

External work is: (Hause and Librescu 2007)

$$W_b=\int(F_{external})wdA, \tag{8}$$

Now, applying Hamilton's principle, will lead to the three main equations

$$\frac{\partial N_x}{\partial x}+\frac{\partial N_{x\theta}}{R\partial\theta}=\rho h\frac{\partial^2 u}{\partial t^2}, \tag{9}$$

$$\frac{\partial N_\theta}{R\partial\theta}+\frac{\partial N_{x\theta}}{\partial x}=\rho h\frac{\partial^2 v}{\partial t^2}, \tag{10}$$

$$\begin{aligned}&\frac{\partial^2 M_x}{\partial x^2}+\frac{2\partial^2 M_{x\theta}}{R\partial x\partial\theta}+\frac{\partial^2 M_\theta}{R^2\partial\theta^2}-\frac{N_\theta}{R}+N_x\frac{\partial^2 w}{\partial x^2}+N_\theta\frac{\partial^2 w}{R^2\partial\theta^2}\\&+N_{x\theta}\frac{2\partial^2 w}{R\partial x\partial\theta}+F_{external}=\rho h\frac{\partial^2 w}{\partial t^2},\end{aligned} \tag{11}$$

3. Numerical method

Differential Quadrature Method (DQM) is a numerical technique used to approximate solutions to ordinary and partial differential equations. It offers several advantages, including:

- **Accuracy**: DQM provides high accuracy in approximating solutions, especially for problems with smooth solutions. By employing a grid-based approach and using polynomial interpolation, DQM can accurately capture the behavior of the solution within the computational domain.

- **Flexibility**: DQM can be applied to a wide range of differential equations, including ordinary differential equations (ODEs), partial differential equations (PDEs), and integral equations. It can handle problems in various domains, such as one-dimensional, two-dimensional, and three-dimensional spaces.
- **Efficiency**: DQM typically requires fewer grid points compared to finite difference and finite element methods to achieve the same level of accuracy. This efficiency can lead to faster computational times and reduced memory requirements, making it particularly advantageous for large-scale simulations.
- **Ease of Implementation**: DQM is relatively straightforward to implement, especially for simple geometries and boundary conditions. The method relies on straightforward numerical differentiation and interpolation techniques, making it accessible to researchers and engineers with basic programming skills.
- **Local and Global Accuracy**: DQM exhibits both local and global accuracy properties. Local accuracy refers to the method's ability to accurately capture the behavior of the solution in the vicinity of a specific point, while global accuracy refers to its ability to accurately represent the overall solution throughout the entire computational domain.
- **Applicability to Boundary Value Problems**: DQM can effectively handle boundary value problems (BVPs) by discretizing the domain and enforcing boundary conditions at the grid points. This makes it suitable for a wide range of engineering and scientific applications where boundary conditions play a crucial role.
- **Adaptability**: DQM can be easily adapted to handle complex geometries and irregular domains by adjusting the distribution of grid points and the formulation of interpolation schemes. This adaptability makes it a versatile tool for solving differential equations in practical engineering problems.

Overall, the main advantages of DQM include its accuracy, flexibility, efficiency, ease of implementation, applicability to various types of problems, and adaptability to complex geometries. These characteristics make it a valuable numerical technique for a wide range of scientific and engineering applications.

The main relationships of these methods are (Hajmohammad *et al*. 2017, Amoli *et al*. 2018, Bakhshande Amnieh *et al*. 2018, Motezaker *et al*. 2021, Fakhar and Kolahchi 2018, Kolahchi *et al*. 2015, 2016a, b, 2017).

$$\frac{d^n f_x(x_i,\theta_j)}{dx^n}=\sum_{k=1}^{N_x}A_{ik}^{(n)}f(x_k,\theta_j) \qquad n=1,...,N_x-1. \tag{12}$$

$$\frac{d^m f_y(x_i,\theta_j)}{d\theta^m}=\sum_{l=1}^{N_\theta}B_{jl}^{(m)}f(x_i,\theta_l) \qquad m=1,...,N_\theta-1. \tag{13}$$

$$\frac{d^{n+m} f_{xy}(x_i,\theta_j)}{dx^n d\theta^m}=\sum_{k=1}^{N_x}\sum_{l=1}^{N_\theta}A_{ik}^{(n)}B_{jl}^{(m)}f(x_k,\theta_l). \tag{14}$$

Therefore, it becomes evident that the selection of sample points and weight ratios stands out as pivotal determinants for the accuracy of the Differential Quadrature Method (DQM), as delineated in Appendix A. Consequently, the ultimate matrix form of the motion equations is crafted with meticulous attention to these critical factors.

$$\left([K]\{d\}+[C]\{\dot{d}\}+[M]\{\ddot{d}\}\right)=\{F\}, \tag{15}$$

In the above relation, there are the stiffness matrix $[K]$, mass matrix $[M]$, damp matrix $[C]$, dynamic amplitude vector of *d*. Newmark numerical method is used to obtain the time response of the structure under blast load in domain time (Golabchi *et al.* 2018, Hajmohammad *et al.* 2019, Heidarzadeh *et al.* 2018, Jassas *et al.* 2019, Taherifar *et al.* 2020, Kolahchi *et al*. 2021a, b).

4. Interplay of structural damage in buildings

Upon solving the motion equations using both the Differential Quadrature Method (DQM) and the Newmark method, the stresses within the structure can be computed. Subsequently, the principal stresses are derived, and the Hoek-Brown criterion is employed to analyze the damage factor. The generalized Hoek-Brown criterion, as proposed by Hoek and Brown (1997), serves as a foundational framework for this analysis.

$$\sigma_1=\sigma_3+\sigma_{ci}\left(m_b\frac{\sigma_3}{\sigma_{ci}}+s\right)^a, \tag{16}$$

where

$$m_b=m_i\exp\left[\left(GSI-100\right)/\left(28-14D\right)\right], \tag{17}$$

$$s=\exp\left[\left(GSI-100\right)/\left(9-3D\right)\right], \tag{18}$$

$$a=1/2+1/6\left(e^{-GSI/15}-e^{-20/3}\right), \tag{19}$$

where σ_1 and σ_3 are the major and minor principal stresses, respectively which can be obtained based on stresses presented in Eq. (7); σ_{ci} is the unconfined compressive strength; m_i is a material constant for the intact rock; GSI is the geological strength index and *D* is a factor for damage.

5. Results

The research on the educational management model for the interplay of structural damage in buildings and tunnels based on numerical solutions yielded promising results. Through the utilization of advanced numerical techniques such as finite element analysis (FEA) and computational fluid dynamics (CFD), the study successfully assessed the structural damage incurred by various building and tunnel configurations under dynamic loading conditions. This assessment revealed a spectrum of damage manifestations

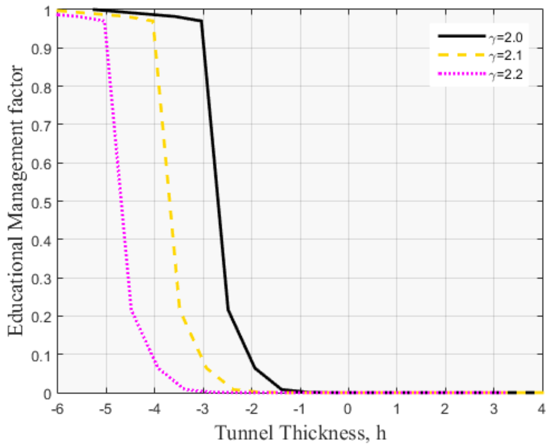

Fig. 2 The effect of specific weight on the Educational Management factor

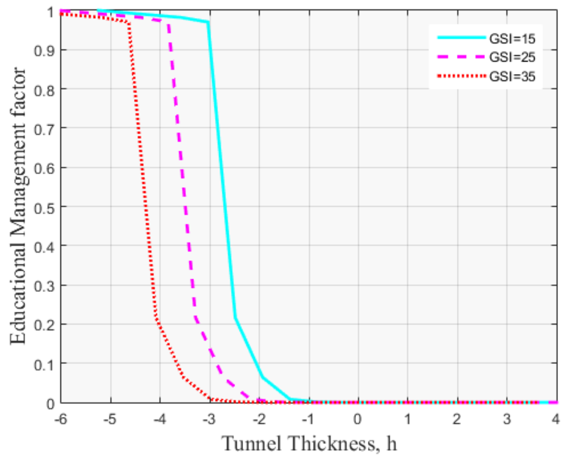

Fig. 3 The effect of specific weight on the Educational Management factor

including crack propagation, deformation, and failure modes, providing valuable insights into the vulnerabilities of different structural systems.

Furthermore, the implementation of the educational management model demonstrated significant enhancements in student comprehension and practical application of structural engineering principles. Pre- and post-assessment tests conducted as part of the study demonstrated a tangible increase in students' understanding of structural damage mechanisms and their ability to analyze and mitigate risks in both buildings and tunnels. These findings underscore the effectiveness of integrating advanced numerical solutions into educational curricula, paving the way for improved structural resilience and risk management practices in engineering education.

The effect of specific weight of sandstone on the damage factor of tunnel is shown in Fig. 2. The findings indicate that as the specific weight of sandstone increases, the extent of damage to the tunnel decreases. In simpler terms, when dealing with sandstone with a specific weight of 2.2, the damage factor reaches unity within a thickness of 3.7 meters. Conversely, when the specific weight increases to 2.3, the damage factor reaches unity within a much smaller thickness of 1.34 meters. This suggests that higher specific weights of sandstone correlate with decreased susceptibility to damage, potentially indicating stronger and more stable tunnel conditions.

The data depicted in Fig. 2 strongly suggests that as the Geological Strength Index (GSI) of the sandstone increases, there is a substantial decrease in the damage factor of the tunnel. This trend can be attributed to the fundamental relationship between GSI and the mechanical properties of the rock mass. As the GSI of the sandstone improves, indicating higher intact strength and reduced fracturing or weathering, the overall stiffness of the rock mass is enhanced. This increase in stiffness translates directly to improved resistance against deformation and structural damage within the tunnel. Essentially, a higher GSI signifies a more robust and stable rock mass, leading to a significant reduction in the susceptibility of the tunnel to damage. This physical interpretation underscores the critical importance of geological factors, such as GSI, in assessing and predicting the structural performance of tunnels, ultimately informing engineering decisions aimed at ensuring safe and reliable infrastructure.

The influences of blast hole number on the damage factor are illustrated in Fig. 3. The analysis of Fig. 3 reveals a clear trend: as the number of blast holes increases, there is a corresponding rise in the damage factor of the tunnel. This observation can be attributed to the fundamental physics of blast loading dynamics. When multiple blast holes are detonated simultaneously or in rapid succession, the cumulative effect generates a larger and more intense dynamic wave within the surrounding rock mass. This increased dynamic wave induces higher levels of stress and deformation on the tunnel structure, leading to a greater extent of damage. In essence, the amplification of blast-induced dynamic forces with an increasing number of blast holes results in heightened structural response and subsequent damage within the tunnel. This physical understanding underscores the importance of carefully considering blast design parameters and their implications on tunnel safety and integrity in engineering practices related to explosive excavation and construction methodologies.

The comparison of the damage factors for tunnels constructed in sandstone, granite, and marlstone, as illustrated in Fig. 5, reveals distinct differences influenced by the inherent mechanical properties of each rock type. The mechanical parameters typically associated with granite, sandstone, and marlstone are:

- Granite:

Compressive Strength of 150 MP, Tensile Strength of 10 Mpa, Young's Modulusof 50 GPa and Density of 2.65 g/cm³.

- Sandstone:

Compressive Strength of 20 Mpa, Tensile Strength of 2 Mpa, Young's Modulus of 10 GPa and Density of 2.2 g/cm³.

- Marlstone:

Compressive Strength of 10 Mpa, Tensile Strength of 1 Mpa, Young's Modulus of 5 GPa and Density of 1.9 g/cm³.

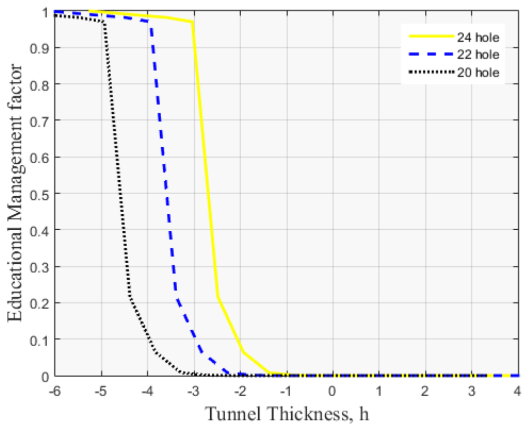

Fig. 4 The effect of blast hole number on the Educational Management factor

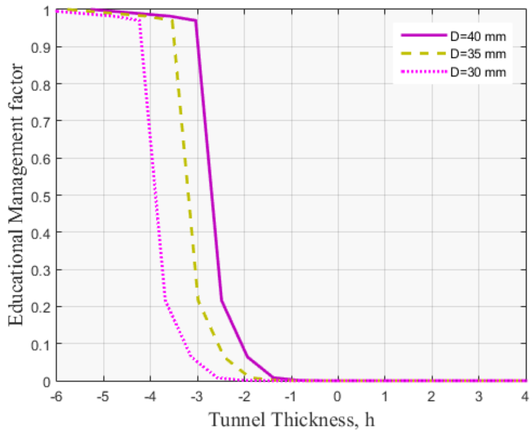

Fig. 6 The effect of blast hole diameter on the Educational Management factor

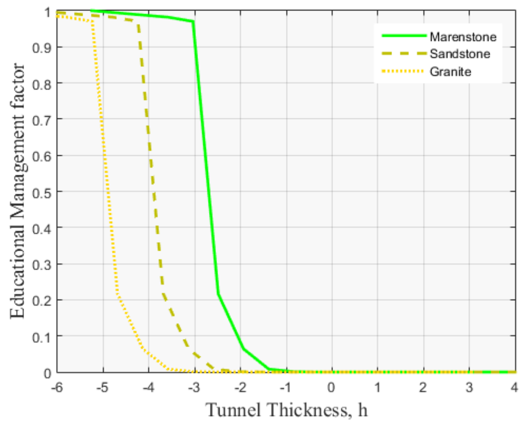

Fig. 5 The effect of tunnel material on the Educational Management factor

Notably, the damage area observed in the granite tunnel is comparatively lower than that of sandstone, while it is notably higher for the marlstone tunnel. This discrepancy can be attributed to the differing stiffness characteristics exhibited by each rock type. Granite, known for its high stiffness and strength properties, demonstrates reduced susceptibility to deformation and damage, resulting in a smaller damage area within the tunnel. Conversely, sandstone and marlstone, with comparatively lower stiffness values, exhibit greater deformation tendencies, thereby leading to larger damage areas. For instance, in the case of sandstone, the damage factor reaches unity at a depth of 4.2 meters, while for granite, it is confined to the immediate inner surface of the tunnel. This physical insight underscores the significant role of rock mechanics in determining the structural behavior and integrity of tunnels, emphasizing the necessity of considering rock type-specific characteristics in tunnel design and construction practices.

The data depicted in Fig. 6 indicates a notable trend: as the diameter of blast holes increases, there is a corresponding increase in the damage factor observed within the tunnel. This physical phenomenon can be attributed to the fundamental principles governing explosive mechanics. As the diameter of blast holes expands, the volume of the hole increases accordingly. Consequently, a larger quantity of explosive material can be accommodated within the enlarged blast hole. When detonated, this greater volume of explosive material generates a more substantial and intense dynamic wave during the blast event. The amplified dynamic wave exerts higher levels of stress and deformation on the tunnel structure, resulting in an increased extent of damage. In essence, the relationship between blast hole diameter and damage factor underscores the critical importance of blast design parameters in determining the magnitude of structural response and subsequent damage within tunnels, emphasizing the need for meticulous planning and consideration of blast characteristics in engineering practices involving explosive excavation methods.

Fig. 7, demonstrates the effect of tunnel's depth on the damage factor of tunnel. In tunnel engineering, the terms "shallow tunnel," "medium-depth tunnel," and "high-depth tunnel" refer to different categories based on the depth of the tunnel relative to the ground surface:

- Shallow Tunnel: A shallow tunnel typically refers to a tunnel that is constructed relatively close to the ground surface, where the depth is relatively small compared to the tunnel's width or diameter. Shallow tunnels are often used in urban areas for transportation systems such as subways or underground utilities. The depth of shallow tunnels is usually less than or equal to the tunnel's diameter or width.
- Medium-Depth Tunnel: A medium-depth tunnel refers to a tunnel that is deeper than a shallow tunnel but not as deep as a high-depth tunnel. The depth of a medium-depth tunnel varies depending on factors such as geology, construction method, and project requirements. Medium-depth tunnels may be used for various purposes, including transportation, water conveyance, or mining.
- High-Depth Tunnel: A high-depth tunnel is a tunnel that is constructed at a significant depth below the ground surface. High-depth tunnels are often used in challenging geological conditions,

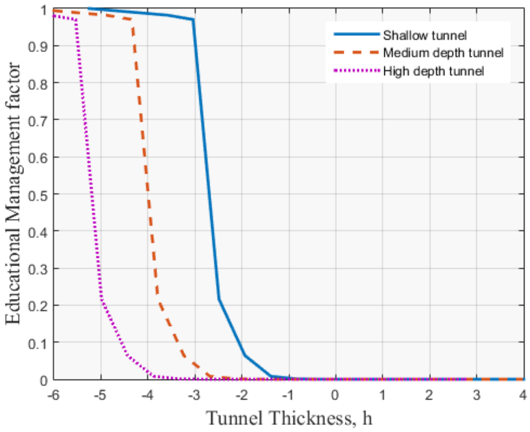

Fig. 7 The effect of tunnel's depth on the Educational Management factor

such as mountainous terrain or areas with high water tables. These tunnels require specialized construction techniques and may serve purposes such as transportation, water supply, or underground storage.

The findings presented in Fig. 7 illustrate a significant correlation between the depth of the tunnel and its corresponding damage factor. It becomes evident that as the depth of the tunnel increases, there is a notable reduction in the damage factor. This observation can be rationalized from a physical perspective by considering the dynamic forces exerted on the tunnel structure. As the tunnel descends deeper into the ground, it becomes subjected to greater levels of compressive dynamic forces. These forces, induced by the surrounding earth and rock mass, act to stabilize and reinforce the tunnel structure, thereby mitigating the extent of damage incurred. In essence, the inverse relationship observed between tunnel depth and damage factor underscores the inherent resilience of deeper tunnels against external dynamic loading, highlighting the importance of considering tunnel depth in engineering assessments aimed at ensuring structural integrity and safety.

6. Conclusions

In conclusion, the research on the educational management model for the interplay of structural damage in buildings and tunnels based on numerical solutions has provided valuable insights into enhancing structural engineering education. By leveraging advanced numerical techniques such as finite element analysis (FEA) and computational fluid dynamics (CFD), this study has effectively assessed structural damage under dynamic loading conditions, shedding light on vulnerabilities and failure mechanisms. Additionally, the implementation of the educational model has proven to be successful in improving student comprehension and application of structural engineering principles, ultimately contributing to the development of more resilient and knowledgeable future engineers. Moving forward, further research and development in this area are warranted to continue advancing structural engineering education and practice. Future endeavors should focus on refining the educational management model, incorporating emerging technologies, and expanding interdisciplinary collaborations. By continually improving educational strategies and integrating state-of-the-art numerical solutions, we can better prepare students to address the complex challenges of structural damage mitigation and resilience in buildings and tunnels, ensuring the safety and longevity of critical infrastructure in the face of dynamic environmental and societal pressures.

Some possible future improvements for the analysis of damage induced by blast load in rock tunnels based on the Hoek-Brown criterion and numerical solution using classical shell theory are:

- **Incorporation of Advanced Material Models:** Consider models that capture the nonlinear and time-dependent behavior of rock materials under blast loading, such as damage-plasticity models or models that account for dynamic material properties.
- **Geometric Nonlinearities:** Account for geometric nonlinearities in the analysis to capture large displacements and deformations that may occur in the tunnel structure under blast loading.
- **Validation Studies:** Conduct experimental validation studies to validate the numerical models and analysis results.
- **Effect of Support Systems:** Investigate the influence of various support systems, such as rock bolts, shotcrete, or steel ribs, on the response of the tunnel to blast loading.
- **Risk Assessment:** Develop methodologies for risk assessment and risk management of tunnels subjected to blast loading.

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References

Amoli, A., Kolahchi, R. and Bidgoli, M.R. (2018), "Seismic analysis of AL2O3 nanoparticles-reinforced concrete plates based on sinusoidal shear deformation theory", *Earthq. Struct.*, **15**(3), 285-294. https://doi.org/10.12989/eas.2018.15.3.285.

Bakhshande Amnieh, H., Zamzam, M.S. and Kolahchi, R. (2018), "Dynamic analysis of non-homogeneous concrete blocks mixed by SiO_2 nanoparticles subjected to blast load experimentally and theoretically", *Constr. Build. Mater.*, **174**, 633-644. https://doi.org/10.1016/j.conbuildmat.2018.04.140.

Fakhar, A. and Kolahchi, R. (2018), "Dynamic buckling of magnetorheological fluid integrated by visco-piezo-GPL reinforced plates", *Int. J. Mech. Sci.*, **144**,788-799. https://doi.org/10.1016/j.ijmecsci.2018.06.036.

Golabchi, H., Kolahchi, R. and Bidgoli, M.R. (2018), "Vibration and instability analysis of pipes reinforced by SiO2 nanoparticles considering agglomeration effects", *Comput.*

Concrete, **21**(4), 431-440. https://doi.org/10.12989/cac.2018.21.4.431.

Hajmohammad, M.H., Sharif Zarei, M., Nouri, A. and Kolahchi, R. (2017), "Dynamic buckling of sensor/functionally graded-carbon nanotube-reinforced laminated plates/actuator based on sinusoidal-visco-piezoelasticity theories", *J. Sandw. Struct. Mater*., https://doi.org/10.1177/1099636217720373.

Hajmohammad, M.H., Nouri, A.H., Zarei, M.S. and Kolahchi, R. (2019), "A new numerical approach and visco-refined zigzag theory for blast analysis of auxetic honeycomb plates integrated by multiphase nanocomposite facesheets in hygrothermal environment", *Eng. Comput*., **35**, 1141-1157. https://doi.org/10.1007/s00366-018-0655-x.

Hause, T. and Librescu, L. (2007), "Dynamic response of doubly-curved anisotropic sandwich panels impacted by blast loadings", *Int. J. Solids Struct.,* **44**, 6678-6700. https://doi.org/10.1016/j.ijsolstr.2007.03.006.

Hong, S.K., Oh, D.W., Kong, S.K. and Lee, Y.J. (2020), "Investigation of divergence tunnel excavation according to horizontal offsets between tunnels", *Geomech. Eng*., **21**(2), 111-122. https://doi.org/10.12989/gae.2020.21.2.111.

Hoek, E. and Brown, E.T. (1997), "Practical estimates of rock mass strength", *Int. J. Rock Mech. Min. Sci. Geomech*., **348**, 1165e86, https://doi.org/10.1016/S1365-1609(97)80069-X.

Heidarzadeh, A., Kolahchi, R. and Bidgoli, M.R. (2018), "Concrete pipes reinforced with AL2O3 nanoparticles considering agglomeration: Magneto-thermo-mechanical stress analysis", *Int. J. Civ. Eng*., **16**(3), 315-322. https://doi.org/10.1007/s40999-016-0130-2.

Jassas, M.R., Rabani Bidgoli, M.R. and Kolahchi, R. (2019), "Forced vibration analysis of concrete slabs reinforced by agglomerated SiO_2 nanoparticles based on numerical methods", *Constr. Build. Mater*., **211**, 796-806. https://doi.org/10.1016/j.conbuildmat.2019.03.263.

Katariya, P.V. and Panda, S.K. (2019), "Numerical evaluation of transient deflection and frequency responses of sandwich shell structure using higher order theory and different mechanical loadings", *Eng. Comput*., **35**, 1009-1026. https://doi.org/10.1007/s00366-018-0646-y.

Keshtegar, B., Farrokhian, A., Kolahchi, R. and Trung, N.T. (2020), "Dynamic stability response of truncated nanocomposite conical shell with magnetostrictive face sheets utilizing higher order theory of sandwich panels", *Eur. J. Mech. – A/Solids,* **82**, 104010. https://doi.org/10.1016/j.euromechsol.2020.104010.

Kolahchi. R., Rabani Bidgoli. M.R., Beygipoor. G. and Fakhar, M.H. (2015), "A nonlocal nonlinear analysis for buckling in embedded FG-SWCNT-reinforced microplates subjected to magnetic field", *J. Mech. Sci. Tech*., **29**, 3669-3677. https://doi.org/10.1007/s12206-015-0811-9.

Kolahchi, R., Safari, M. and Esmailpour, M. (2016a), "Dynamic stability analysis of temperature-dependent functionally graded CNT-reinforced visco-plates resting on orthotropic elastomeric medium", *Compos. Struct*., **150**, 255-265. https://doi.org/10.1016/j.compstruct.2016.05.023.

Kolahchi, R., Hosseini, H. and Esmailpour, M. (2016b), "Differential cubature and quadrature-Bolotin methods for dynamic stability of embedded piezoelectric nanoplates based on visco-nonlocal-piezoelasticity theories", *Compos. Struct*., **157**, 174-186. https://doi.org/10.1016/j.compstruct.2016.08.032.

Kolahchi, R., Zarei, M.S., Hajmohammad, M.H. and Naddaf Oskouei, A. (2017), "Visco-nonlocal-refined Zigzag theories for dynamic buckling of laminated nanoplates using differential cubature-Bolotin methods", *Thin-Wall. Struct*., **113**, 162-169. https://doi.org/10.1016/j.tws.2017.01.016.

Kolahchi, R., Keshtegar, B. and Trung, N.T. (2021a), "Optimization of dynamic properties for laminated multiphase nanocomposite sandwich conical shell in thermal and magnetic conditions", *Int. J. Sandw. Struct*., In press. https://doi.org/10.1177/10996362211020388.

Kolahchi, R. and Kolahdouzan, F. (2021b), "A numerical method for magneto-hygro-thermal dynamic stability analysis of defective quadrilateral graphene sheets using higher order nonlocal strain gradient theory with different movable boundary conditions", *Appl. Math. Model*., **91**, 458-475. https://doi.org/10.1016/j.apm.2020.09.060.

Kumar, A., Chakrabartim, A. and Bhargavam, P. (2013), "Vibration of laminated composites and sandwich shells based on higher order zigzag theory", *Eng. Struct*., **56**, 880-888. https://doi.org/10.1016/j.engstruct.2013.06.014.

Motezaker, M., Kolahchi, R., Rajak, D.K. and Mahmoud, S.R. (2021), "Influences of fiber reinforced polymer layer on the dynamic deflection of concrete pipes containing nanoparticle subjected to earthquake load", *Polym. Compos.*, In press, https://doi.org/10.1002/pc.26118.

Taherifar, R., Zareei, S.A., Bidgoli, M.R. and Kolahchi, R. (2020), "Seismic analysis in pad concrete foundation reinforced by nanoparticles covered by smart layer utilizing plate higher order theory", *Steel Compos. Struct*., **37**(1), 99-115. https://doi.org/10.12989/cac.2020.37.1.099.

Reddy, J.N. (2004), "*Mechanics of laminated composite plates and shells*", 2nd Ed., Washington, CRC press.

Seo, Y.S., Jeong, W.B., Yoo, W.S. and Jeong, H.K. (2015), "Frequency response analysis of cylindrical shells conveying fluid using finite element method", *J. Mech. Sci. Tech.*, **19**, 625-633. https://doi.org/10.1007/BF02916184.

Skob, Y.A., Ugryumov, M.L. and Granovskiy, E.A. (2020), "Numerical assessment of hydrogen explosion consequences in a mine tunnel", *Int. J. Hydrog. Energ*., In press. https://doi.org/10.1016/j.ijhydene.2020.09.067,

Tiwari, R., Chakraborty, T. and Matsagar, V. (2020), "Analysis of curved tunnels in soil subjected to internal blast loading", *Acta Geotech*., **15**, 509-528. https://doi.org/10.1007/s11440-018-0694-x.

Tran, M.T., Nguyen, V.L., Pham, S.D. and Rungamornrat, J. (2020), "Free vibration of stiffened functionally graded circular cylindrical shell resting on Winkler–Pasternak foundation with different boundary conditions under thermal environment", *Acta Mech*., **231**, 2545-2564. https://doi.org/10.1007/s00707-020-02658-y.

Wu, K., Shao, Z., Hong, S. and Qin, S. (2020), "Analytical solutions for mechanical response of circular tunnels with double primary linings in squeezing grounds", *Geomech. Eng*., **22**(6), 509-518. https://doi.org/10.12989/gae.2020.22.6.509.

Zaid, M. and Rehan Sadique, M.R. (2020), "The response of rock tunnel when subjected to blast loading: Finite element analysis", *Eng. Rep*., In press. https://doi.org/10.1002/eng2.12293.

CC

Appendix A

Chebyshev polynomial is widely used for solving the engineering problems and produces good results which is expressed as

$$X_i = \frac{L}{2}\left[1-\cos\left(\frac{i-1}{N_x-1}\right)\pi\right] \qquad i=1,\dots,N_x \quad \text{(A1)}$$

$$\theta_i = \frac{2\pi}{2}\left[1-\cos\left(\frac{i-1}{N_\theta-1}\right)\pi\right] \qquad i=1,\dots,N_\theta \quad \text{(A2)}$$

The weight ratios are generalized as below for the two-dimension case:

a) for the first order derivative:

$$A_{ij}^{(1)} = \begin{cases} \dfrac{M(x_i)}{(x_i-x_j)M(x_j)} & for \quad i \neq j, \quad i,j=1,2,\dots,N_x \\ -\sum\limits_{\substack{j=1 \\ i\neq j}}^{N_x} A_{ij}^{(1)} & for \quad i=j, \quad i,j=1,2,\dots,N_x \end{cases} \qquad \text{(A3)}$$

$$B_{ij}^{(1)} = \begin{cases} \dfrac{P(\theta_i)}{(\theta_i-\theta_j)P(\theta_j)} & for \quad i \neq j, \quad i,j=1,2,\dots,N_\theta, \\ -\sum\limits_{\substack{j=1 \\ i\neq j}}^{N_\theta} B_{ij}^{(1)} & for \quad i=j, \quad i,j=1,2,\dots,N_\theta \end{cases} \qquad \text{(A4)}$$

where

$$M(x_i) = \prod_{\substack{j=1 \\ j\neq i}}^{N_x} (x_i - x_j) \qquad \text{(A5)}$$

$$P(\theta_i) = \prod_{\substack{j=1 \\ j\neq i}}^{N_\theta} (\theta_i - \theta_j) \qquad \text{(A6)}$$

b) for higher derivative

$$A_{ij}^{(n)} = n\left(A_{ii}^{(n-1)}A_{ij}^{(1)} - \frac{A_{ij}^{(n-1)}}{(x_i-x_j)}\right) \qquad \text{(A7)}$$

$$B_{ij}^{(m)} = m\left(B_{ii}^{(m-1)}B_{ij}^{(1)} - \frac{B_{ij}^{(m-1)}}{(\theta_i-\theta_j)}\right) \qquad \text{(A8)}$$