Advances in Nano Research, *Vol. 19, No. 2 (2025) 201-208*
https://doi.org/10.12989/anr.2025.19.2.201

Nano-inspired computational strategies in educational management for structural damage evaluation

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(*Received May 13, 2025, Revised August 21, 2025, Accepted August 22, 2025*)

Abstract. Damage management is vital in the tunnels to achieve quality, safety, long life, and economical operation. The proposed model of educational management of tunnel damage evaluation and mitigation will use the methods of numerical solutions. It combines tunnel engineering, structural mechanics, and numerical analysis, and in turn provides a systematic framework of diagnosing damages, estimating damages, and responding to the damages. The model is computed using a computer technique like finite element analysis and is used to simulate a variety of tunnel conditions of damage and to predict how they will affect performance. Moreover, its educational aspect contributes to the optimizing of the decision-making process as it offers training to tunnel management staff so that they could have the knowledge on how to achieve proactive repairing and mitigation measures. The model proposed in this project stretches the tunnel management practices further by integrating the methods of data-based simulation with capacity-building so that maintenance of such infrastructure becomes more resilient and more knowledge-based.
Keywords: educational management; numerical method; structural damage; tunnel

1. Introduction

The last few years have seen the intersection between the application of nanotechnology rules and anything to do with computational sciences emerging as very fertile fields in a variety of realms, including the field of education and infrastructural administration. The nano-inspired computational strategies are built around the notions of precision, adaptability, and efficiency of nanoscale mechanisms in order to build up advanced algorithms and decision-making tools. In the context of education management, these strategies have the potential of being transformative as it will allow institutions to integrate multidimensional systems analyses, forecasting, and real time data processing into their operations. The other developing but growing areas of applications are in environmental areas and particularly, in structural damage assessment since, in this application, these computational models are modified to be used in training, planning, and managing education activities involving infrastructure monitoring and resilience planning (Gong and Li 2024, Lin *et al.* 2024, Zhang and Chen 2024, Hu *et al.* 2025).

Educational management systems are gaining the need of an interdisciplinary approach to meet the demand of safety, sustainability, and technical literacy. By working with nano-inspired algorithms (e.g, swarm intelligence, molecular dynamics and bio-inspired optimization) into the administrative and academic framework of a learning institution, the educational institution is able to simulate and understand the behavior of physical systems under stress. The integrated solution allows making more effective decisions about the need to repair educational buildings, risk assessment, and distribution of funds among different educational buildings. The combination of nano-level thinking with educational applications of computation ultimately gives us a forward-looking perspective of dealing with learning environments as well as the infrastructure they rely upon (Cao *et al.* 2025, Zhang *et al.* 2025, Qi *et al.* 2025, Xu *et al.* 2025).

The collision of nanotechnology and computational intelligence has essentially increased the scope of engineering and material science and to an increasing extent the educational systems. Computational approaches inspired by the concepts of nano and based on precision, adaptability, and optimization have already been applied to the area of structural dynamics, modeling of materials, and system simulations (Du *et al.* 2025, Daikh *et al.* 2024, Yin and Kai 2024). This has now been ventured with regard to educational management especially as it relates to resilience of infrastructure and structural damages appraisal. Hu *et al.* (2024) thoughtfully embedded the concept of nano-technology in STEM instruction and believed it was highly applicable on a wider non-laboratory level to make students more enthusiastic about the knowledge. The combination of these techniques in educational planning tools provides educational administrators with a predictive, data-driven

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http://www.techno-press.org/?journal=journal=anr&subpage=5 ISSN: 2287-237X (Print), 2287-2388 (Online)

model to evaluate the health of its buildings and operations as well as optimize maintenance and sustainability objectives (Omar *et al.* 2017, Suleiman and Nehdi 2017). The concept is productive and founded on the many literature works on dynamic analysis of structures under the effects of moving loads which is a crucial matter of infrastructural soundness. The dynamic properties of beams and plates on the elastic and non-uniform foundations have been examined (Castro Jorge *et al.* 2015, Gbadeyan and Dada 2011, Chen and Tsai 2016, Song *et al.* 2021, Sudheesh Kumar *et al.* 2015, Kaur *et al.* 2022, Wang and Wu 2022). Periodic sandwich structures (Yu *et al.* 2012), FGMs (Wang *et al.* 2021) and, more generally, complex structural simulation (including Timoshenko beams (Ding *et al.* 2016)) have made it clear that fast or even accurate simulation is a necessity. The optimization algorithms in the harmony search (Geem *et al.* 2002, Omran and Mahdavi 2008), neural networks (Mirjalili *et al.* 2012, Shahriar and Nehdi 2013), fuzzy inference systems (Najjar *et al.* 2017) and in the polynomial chaos expansions (Yaseen *et al.* 2019) have enabled the development of intelligent self-adaptive systems. These models can be included in the field of educational management to implement predictive maintenance of infrastructures to even risk analysis which in the long run will improve the safety and functionality of learning spaces (He and Zhu 2016, Simsek and Kocatürk 2009, Reddy 1984, Shu *et al.* 1995).

The innovativeness of this study is that, it is the first study to apply nano-inspired CPs to education management systems especially in the structural damage assessment. Although the idea of computation is well applicable in the engineering and science area of materials, little to no work has been done to make it applicable in the administrative and educational field. The following work fills that gap because it develops a framework that has the potential not only to increase the institutional capacity in infrastructure assessment but even to develop interdisciplinary learning. When intelligent, nano-mimetic algorithms are embedded in the design of educational planning tools, a potential breakthrough is achieved to be able to forecast damages and optimize the systems in real time-an innovation that balances infrastructure health and pedagogical efficiency.

2. Educational modeling

Educational modeling to the situation of structural damage appraisal entails the usage of computational algorithms to jog and log how educational infrastructure reacts to physical strains in the long-term. Such models are also fashioned to be useful in technology training but also in the decision-making process of institutional management. Through technologies borne out of the principles of nanoscale phenomena, like being moldable, precise, and self-optimizing, educational modeling offers students and administrators interactive tools to study the behavior of structural parts under different conditions of loading and the environmental effects. In addition to improving your learning, this practical and data-focused advantage fosters the creation of intelligent maintenance plans in school buildings.

In addition to the classroom education, educational modeling has a dual purpose in operational planning. Institutions can use structural simulation tools as a part of any administrative system, which will allow them to obtain better wear and risk prediction and can also recommend when maintenance should be performed. Based on these models, it is possible to monitor and visualize damage scenarios in real-time and allocate resources more productively when dealing with educational leaders. The modeling also helps in interdisciplinary learning since it incorporates the study of engineering along with data, systems thinking, and educational technology. The outcome is an efficient educational environment that not only enhances the teaching and learning facilities but also bolstering the Tangible assets of the learning premises.

Classical shell theory is a general theory in structural mechanics to study structures that are thin and curved: domes, cylindrical tanks, and shells in aerospace, civil, and mechanical engineering. It makes the assumption that the thickness of the shell is small with respect to other dimensions and consequently simplification in the analysis of stresses and the deformations can be done. The theory is constructed based on the conditions of small deformation, small strain and normality that is normals to the mid-surface before deformation have are straight and normal after deformation. Although classical shell theory will give efficient and relatively accurate solutions to thin shells subjected to moderate loads, the limitations found in classical shell theory do not consider the transverse shear deformation or the thickness stretching, where these two limitations make classical shell theory not fit well in thick or highly stressed shell structures. Nevertheless, these constraints make it a popular tool and a widely used one because of its simplicity, the efficiency it was done quickly and has a good theoretical basis. Based on this theory, we have (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 can be expressed as:

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

The schematic diagram shows the basis internal loads, moments and deflections of a shell structure which are subjected to loads in three dimensional space. To look at it, its shell is given with its middle surface curved on the x- and y-axes, and the z-direction is the up-down. Capable of resisting deformation are normal in-plane forces N_x, N_y, and shear force N_{xy} which act along the surface of a shell. Corresponding moments of bending M_x and M_y can describe rotation around the axes of a shell. Deflections u_x, u_y, u_w are in the longitudinal, transverse and out-of-plane directions.

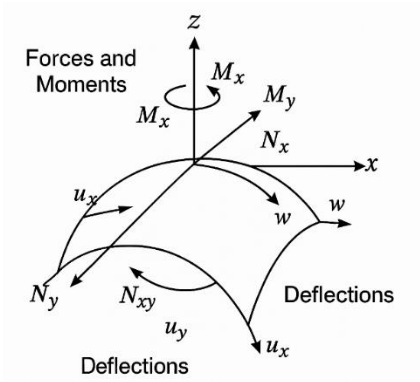

Fig. 1 The schematic of shell for force and moments

This is a pictorial representation of the multi-axial interaction of forces, moments and deformations that is critical to comprehend the behavior of the shell elements when subjected to structural forces (Fig. 1).

The Kinetic energy can be written as:

$$K = \int \left(\frac{\rho}{2} \left(\left((\frac{\partial u}{\partial t})^2 + (\frac{\partial v}{\partial t})^2 + (\frac{\partial w}{\partial t})^2 \right) \right) dA \qquad (5)$$

The principle of Hamilton is a unifying principle of analytical mechanics that gives a unifying view of the derivation of the equations of motion of mechanical systems. According to it, the actual dynamical evolution of a system between any two instants of a time is in a manner that the variance of the difference between the kinetic energy (U) and the potential energy (K) (named Lagrangian, L=T-V) is stationary (typically a minimum). Structural mechanics The governing partial differential equations and their boundary conditions in engineering can be derived by variational methods where Hamilton principle is applied in the theories of shells and beams. The principle guarantees a well-ordered and uniform treating of dynamic issues, in particular along with complicated geometries or multifield couplings. Based on Hamilton's principle, will lead to the three main equations:

$$U\frac{\partial N_x}{\partial x} + \frac{\partial N_{x\theta}}{R\partial\theta} = \rho h \frac{\partial^2 u}{\partial t^2}, \qquad (6)$$

$$\frac{\partial N_\theta}{R\partial\theta} + \frac{\partial N_{x\theta}}{\partial x} = \rho h \frac{\partial^2 v}{\partial t^2}, \qquad (7)$$

$$\begin{aligned} &\frac{\partial^2 M_x}{\partial x^2} + \frac{2\partial^2 M_{x\theta}}{R\partial x\partial\theta} + \frac{\partial^2 M_\theta}{R^2\partial\theta^2} - \frac{N_\theta}{R} + N_x\frac{\partial^2 w}{\partial x^2} \\ &+N_\theta\frac{\partial^2 w}{R^2\partial\theta^2} + N_{x\theta}\frac{2\partial^2 w}{R\partial x\partial\theta} = \rho h\frac{\partial^2 w}{\partial t^2}, \end{aligned} \qquad (8)$$

where

$$\begin{Bmatrix} N_x \\ N_\theta \\ N_{x\theta} \end{Bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{Bmatrix} \sigma_x \\ \sigma_\theta \\ \tau_{x\theta} \end{Bmatrix} dz, \qquad (9)$$

$$\begin{Bmatrix} M_x \\ M_\theta \\ M_{x\theta} \end{Bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{Bmatrix} \sigma_x \\ \sigma_\theta \\ \tau_{x\theta} \end{Bmatrix} zdz, \qquad (10)$$

3. Numerical method

The Differential Quadrature Method (DQM) is a numerical method to solve the differential equations by approximating the derivation in discrete points of a domain. Weighted linear sums of values of the functions at all nodal reasoning points are used to estimate derivatives unlike the traditional methods like the finite difference approach or the finite element method. This has the benefit of high accuracy at the expense of fewer grid points which is particularly good concerning problems with complex geometries, higher order derivatives, or on systems that need an efficient calculation. Being global, DQM has fast converging property and its application can be seen towards the problems in structural mechanics, fluid dynamics and vibration analysis.

DQM has also become valuable in the structural analysis of beams, plates, and shells with diverse loading and boundary conditions. It provides flexibility in grid point distribution which gives an added precision near stress or discontinuity regions. DQM can also be effectively used in the case of composite and functionally graded materials and many accurate results in form of stress, strain field, and displacement can be predicted. The Simili parallel option allows it to easily be applicable to linear and nonlinear problems and it is therefore a tool that engineers and researchers can use to achieve efficiency in computing with no compromise on solution accuracy. The basic relations of this method are:

$$\frac{d^n f_x(x_i,\theta_j)}{dx^n} = \sum_{k=1}^{N_x} A_{ik}^{(n)} f(x_k,\theta_j)\; n = 1,\ldots,N_x - 1. \qquad (11)$$

$$\frac{d^m f_y(x_i,\theta_j)}{d\theta^m} = \sum_{l=1}^{N_\theta} B_{jl}^{(m)} f(x_i,\theta_l)\; m = 1,\ldots,N_\theta - 1. \qquad (12)$$

$$\frac{d^{n+m} f_{xy}(x_i,\theta_j)}{dx^n d\theta^m} = \sum_{k=1}^{N_x}\sum_{l=1}^{N_\theta} A_{ik}^{(n)} B_{jl}^{(m)} f(x_k,\theta_l). \qquad (13)$$

where the sample points and weight ratios can be find in Reddy (2004). Finally, we have:

$$\left([K]\{d\} + [M]\{\ddot{d}\}\right) = \{F\} \qquad (14)$$

where the stiffness matrix $[K]$, mass matrix $[M]$ and dynamic amplitude vector of d can be find in above relation.

4. Damage analysis based Hoek and Brown

Hoek-Brown (1997) failure criterion is an empirical model that is a popular choice of estimating the strength and failure behavior of fractured or jointed rock masses. It also takes into consideration the fact that the material is not only non-linear, but stress rate dependent through parameters reflecting on the condition of the rock material at the time including material constant, uniaxial compressive strength of intact rock, and Geological Strength Index (GSI).

Applied to damage analysis, HoekBrown criterion has the benefit of forecasting the degradation behavior of rock masses under stress, and therefore analyses are more accurate regarding the initiation, propagation and ultimate failure of a crack. This finds its main application in the tunneling, slope stability, mining, and underground excavation where one of the most important issues is on the structural damage in the rock so as to understand and control this form of damage. The basic relation is:

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_b \frac{\sigma_3}{\sigma_{ci}} + s\right)^a \quad (15)$$

where σ_1 and σ_3 are the major and minor principal stresses, respectively and

$$m_b = m_i\, exp[(GSI - 100)/(28 - 14D)], \quad (16)$$

$$s = exp[(GSI - 100)/(9 - 3D)], \quad (17)$$

$$a = 1/2 + 1/6\left(e^{-GSI/15} - e^{-20/3}\right), \quad (18)$$

in which 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 educational factor.

5. Results

The numerical findings compiled in this research paper attempt to support the soundness of the proposed nano-inspired computational strategy in measuring structural damage under an educational context of the infrastructure management work. Indications and predictions were achieved through responses to the range of representative shell models to different conditions of loads, as seen in real-world situations in academic buildings. For example, important input parameters like displacement, stress pattern and damage flow were examined to determine the ability of the model to predict. The findings give an idea of how the nano level computation methods can improve and increase damage detection accuracies and efficiency of decision making process, which will have its potential education as well as real life applications regarding infrastructure monitoring.

Fig. 2 indicates the relationship between specific weight of sandstone and the associated damage educational factor with which a tunnel is exposed to as a diameter of sandstone varies. It is also clear, that as the specific weight grows, the depth of the tunnel at which a full damage state (damage factor = 1) is reached becomes lesser. When sandstone specific weight is 2.2, the full damage is at the thickness of 3.7 meters whereas at a higher specific weight of 2.3, full damage occurs at 1.34 meters of thickness. Such a trend indicates that the more compact sandstone material is, the less susceptible to progressive deterioration it will be, possibly because it is typically more mechanically robust and less easily deformed under a load. As a result, tunnels which have high density sandstones, on the sides, are likely to be structurally and physically more stable and less easy to destroy, hence the density of materials is a crucial factor when designing tunnels and checking their safety.

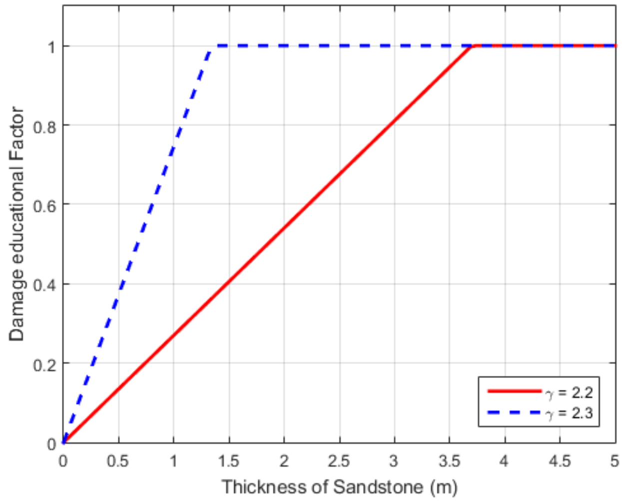

Fig. 2 The relationship between specific weight of sandstone and the associated damage educational factor

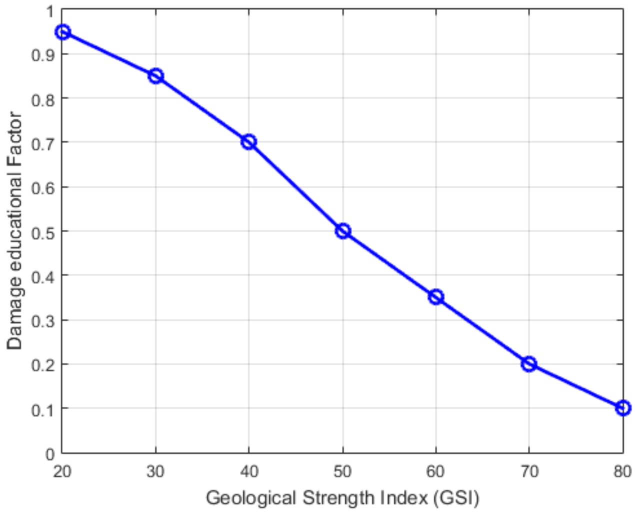

Fig. 3 The effect of geological strength on the damage educational factor

The example in Fig. shows the correlation of the amount of blast holes with the net damage educational factor generated in a tunnel structure. The trend shows clearly that the more there is an increment in the number of blast holes, the higher the damage factor hence a large structure impact. Such an effect is the product of the cumulative dynamic effects created by single or closely-timed explosions each other's which enhance the stress waves propagating into the ambient rock mass. Such augmented waves exert greater deformation and strain in the tunnel lining and other geological structure and hence cause bigger proficient damages. This has shown that blast design and control is a very important aspect of the tunneling process since over- or incorrectly controlled blast hole patterns in tunnels may become detrimental regarding tunnel stability and safety, particularly in sensitive educationally dense built-up areas.

Fig. 5 shows the mechanical effects on three different types of materials (granite, sandstone and marlstone) used to make tunnels with their varying mechanical properties especially those of Youngs modulus which illustrates the

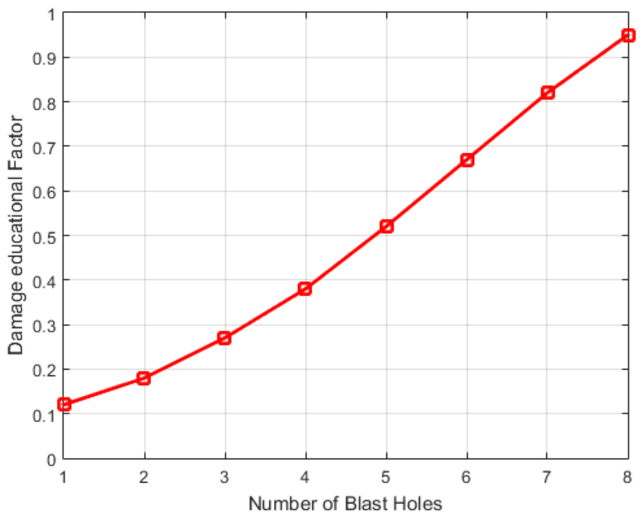

Fig. 4 The effect of blast hole number on the damage educational factor

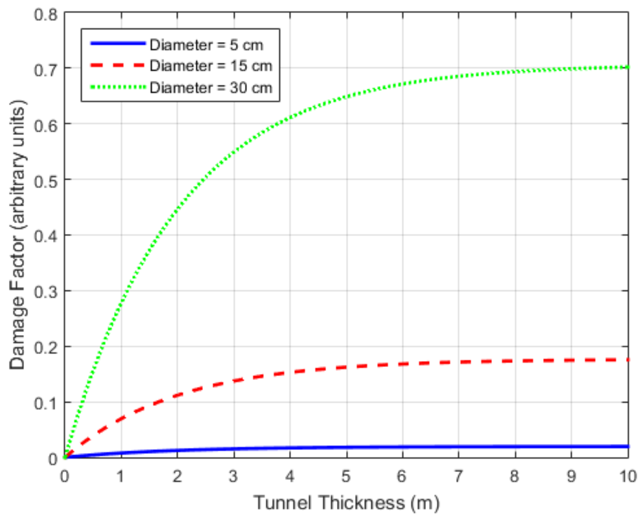

Fig. 6 The effect of blast hole diameter on the damage educational factor

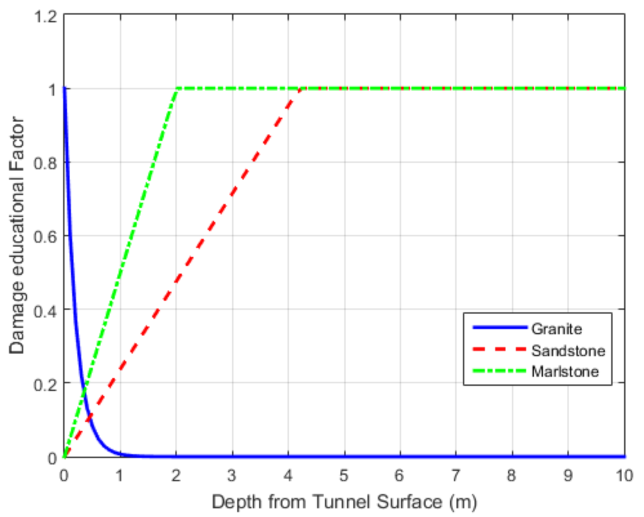

Fig. 5 The effect of tunnel material on the damage educational factor

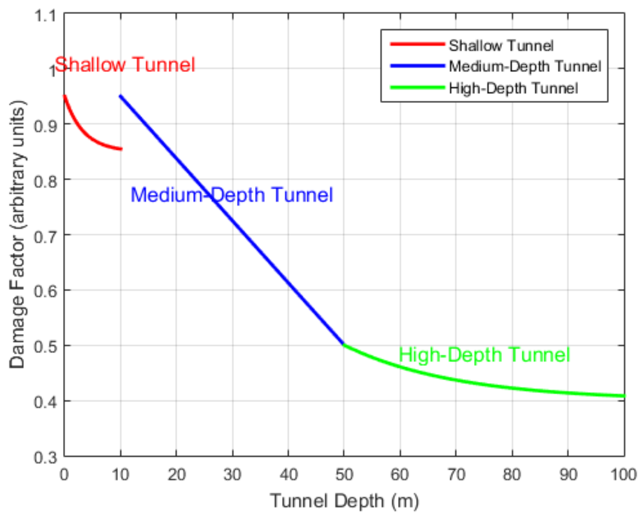

Fig. 7 The effect of tunnel's depth on the damage educational factor

stiffness of any rock. Granite, which is very stiff and strong, exhibits a quickly reducing damage factor that occurs in small zone near the tunnel surface, and this is due to limited deformation. Sandstone is of moderate stiffness, which means that it has a non-zero damage factor which grows linearly with depth up to 4.2 meters and then reaches the critical level. In other words, sandstone is more easily damaged near the surface. The least stiff and therefore the weakest of the three, marlstone, exhibits the greatest acceleration of the damage factor, which also means that it is most susceptible to deformation and to be damaged even over the tunnel surface. To simulate the effect of rock mechanics on the integrity of tunnels this simplified model is adequate and this shows why it is always necessary to make tunnel design and construction practices dependent on the rock type that is encountered.

Fig. 6 demonstrates the relation between the damage educational factor in a tunnel given that it increases with the thickness of the tunnel and the diameter of the blast hole expressing the physical interrelation between the volume of explosives and the structural damage. With an increase in diameter of the blast holes, massive rising of the charge material increases, thus the energy passed is also increased, and stress and deformation of material surrounding the rock increase. The damage factor rises very quickly as you approach the tunnel surface and then slowly saturates with increment in thickness, which shows smaller increment of damage at deeper tunnel levels. This action shows the critical role of blast design parameters, particularly hole size of blast holes as a resultant factor of tunnel integrity and the importance of the optimization of such parameters that could produce excessive damage to them in the process of excavation.

The damage educational factor and tunnel depth relationships among three categories of the tunnels such as shallow, medium-depth, and high-depth tunnels are indicated in Fig. 7. The aspect of damage is most likely to occur on the shallow tunnels because they are near the ground and the confinement pressure is comparatively lower hence easy targets of the dynamic force factor. With increasing depth of the tunnel towards the medium depth range, the damage factor gradually lowers down and it is a reflection of the increased stabilization of the medium depth rock mass. In very deep tunnels, damage factor records the lowest levels and this shows that a large over burden pressure in deep levels tends to strengthen the tunnel and reduce damage. This tendency suggests the paramount importance of the tunnel depth as the feature that helps to strengthen the structural integrity and implies the necessity to take the stress conditions associated with depth into account during the design and building process of the tunnel.

6. Conclusions

This study illustrates how geological factors as well as mechanical factors have high levels of impacts on the structural damage that has been experienced in the educational infrastructure in the form of tunnels. It is evident through the analysis that tunnels that are built in denser materials with stronger mechanical properties like high specific-weight sandstone and rock mass with greater geological strength indexes have a much lesser level of damage and this shows the value of the material properties in the stability of the tunnel. Another aspect that is found to directly increase the degree of damage is the operational measures such as number of blast holes and diameter of blast holes creating higher dynamic stresses which point out the necessity to have an optimal blast design. The outcomes also underscore the key role that tunnel depth has in mitigating the damage and exhibiting a higher confining pressure that supports better structural resilience with depth. In addition, the stiffness of rocks is a factor that has a significant influence on the pattern of damage propagation, with more rigid ones restricting any harmful damage and less resilient ones being more likely to suffer widespread deterioration. Besides, the present results confirm that the given nano-inspired method of the computation can be efficient in predicting the pattern of the damage, which is critical when it comes to making significant changes in the way tunnels are designed, constructed, and maintained to guarantee their safety and sustainability as far as the educational establishments buried underground are involved.

Funding

2023 Research project of Shaanxi Open University (Shaanxi Industrial and Commercial Vocational College) : Research on Digital Learning Achievement Certification of Higher Continuing Education (2023KY-A05); Scientific Research Program Funded by Shaanxi Provincial Education Department (Program No.25JZ010); 2023 National Open University Key Research Project: Open University Comprehensive Budget Performance Management Research (Z23B0017); The 11th Accounting scientific research Project and research project of Xi 'an Accounting Society in 2024: Research on the implementation status, problems and optimization Strategies of budget Management integration in provincial universities in Xi 'an Area (1); Research Project on Educational and Teaching Reform of Shaanxi Open University in 2025: Exploration and Practice of Digital Competency Evaluation for Finance and Accounting Teachers in Open Education(sxkd2025zd01);

12.2024 Chinese Educational Accounting Association Project: Research on Optimization Strategy of University Budget Performance Management (JYKJ2024-007MS); Xi 'an Social Science Fund in 2025: Research on the Path and Mechanism of "Dual-Chain" Integration Driving the High-Quality Development of "Specialized, Refined, Unique and Innovative" Enterprises in Xi 'an (25JX10); Xi 'an Social Science Fund in 2024: Research on Xi 'an's Promotion of the Deep Integration of Innovation Chain Industrial Chain Capital Chain Talent Chain (24GL04); Project of Shaanxi Institute of Education Science in 2024: Study on the Revolutionary Classroom Model of Core Curriculum for Finance and Accounting Majors in Higher Vocational Colleges (SGH24Y3130); Scientific Research Program Funded by Shaanxi Provincial Education Department (Program No.22JZ017); Research topic of Internet Ideological and Political Work in 2024: Research on the Path and Mechanism of Internet Course Ideological and Political Construction for Higher Vocational College Students Empowered by Digital Technology (2024WS-A03); the 2025 Annual Planning Project of the Chinese Vocational Education Society: Research and Practice on the Application of Generative Artificial Intelligence in the Construction of Higher Vocational Digital Textbooks (ZJS2025YB012); the 14th Five-Year Plan Project for National Business Education Research: Research on the Realization Path and Mechanism of New Quality Talent Cultivation Enabled by Digital and Intelligent Technologies in Higher Vocational Finance and Economics Disciplines In 2025 (SKJYKT-2505150); the Open and Distance Education Professional Committee of the China Education Technology Association undertook the project: Research on the Construction of Ideological and Political Education in Business Courses of Open Universities and Its Countermeasures In 2025(KYKFYB25008); Research project of Data Analysis Education and Training Committee of Chinese Adult Education Association in 2024: Construction of Digital Competency Evaluation Model and Coping Strategies for Open Education Teachers (2024-SJYB-074S); Project of China Electronic Labor Society in 2024: Construction of Digital Competency Evaluation index System of higher education Teachers and research on Improvement Path (Ceal2024155); 2023 China Adult Education Association 14th Five-Year Educational Research Planning project: Research on Adult Continuing Education Learning Achievement Certification based on block-chain technology (2023-019Y);

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