International Journal of Research in Engineering, Science and Management
Volume 6, Issue 4, April 2023
https://www.ijresm.com | ISSN (Online): 2581-5792

Literature Review on Tunnel Squeezing Deformation Control and the Use of Yielding Elements in Shotcrete Linings

Rahul Kumar*
Resident Engineer, Excavation Specialist, Rodic Consultant Pvt. Ltd., Delhi, India

***Abstract*: The shotcrete lining exhibits significant resistance but minimal malleability. To combat tunnel squeezing deformations, ductile lining, which employs yielding components, offers a viable solution. This review article aims to outline the development of this concept and evaluate the research conducted in this domain. The paper commences with a brief introduction to tunnel squeezing deformations. It then summarizes the supportive mechanism and advantages of ductile lining in tunnels excavated in squeezing ground conditions. The succeeding section outlines the four primary categories of yielding elements employed in shotcrete lining and presents their fundamental structures and mechanical properties. The impact of yielding element parameters on supportive effects is discussed and then applications of the various yielding element in different places with slight modification as per the demand of the work has been reviewed.**

***Keywords*: squeezing, yielding element, shotcrete lining, stress controller element, splinters, rock deformation.**

1. Introduction

Squeeze is characterized by long-lasting large displacements, but does not provide a threshold for displacement size or displacement duration. Excessive tunnel convergence is often the case when tunnel engineers perform deep excavations in confined ground [1-7]. Rock deformation occurs slowly and can persist for varying periods of time, from weeks to months and even he years after drilling is complete [8-15]. A rigid tunnel shotcrete lining that strictly limits rock deformation cannot withstand the large overburden pressures caused by large rock deformations [16,17]. As a result, splinters and cracks in the shotcrete and even severe tunnel collapses are often observed [18,19]. It is almost impossible to contain the strain energy involved by using heavier liners under such conditions [20–22]. More attention is being paid to the use of compliant his elements in shotcrete linings resulting in so-called "ductile linings" to avoid failure of shotcrete linings in deep excavations by compressing the ground. First, tunnel engineers split the shotcrete shell into several segments, leaving longitudinal gaps beforehand to accommodate large rock deformations without damaging the shotcrete. However, with this method, the internal forces around the formwork segments were not significantly transferred across these reserved gaps, resulting in a significantly reduced resistance of the shotcrete shell [23]. A proposal to address the problem of considerable rock deformation and transmission of internal forces from the shotcrete lining was to replace the open gap with a flexible element of ductile lining. Because compliant elements have greater deformability than shotcrete, shotcrete linings are more resistant and can accommodate rock deformation controlled by compressive deformation [24–29]. The first application of ductile lining was in 1994 at the Gargenberg Tunnel in Austria. There, groups of axially loaded steel pipes with manufactured localized weakness were used as compliance elements to successfully overcome large crushing deformations of shotcrete linings [30]. Over the last two decades, fiberglass reinforced plastic (FFU) elements [16], telescopic compliance elements [36], and liner tension control elements [37]. These compliant elements are the Tauern Tunnel in Austria [38], the Lyon-Turin Base Tunnel connecting France and Italy [31,39], and the Yangshan Tunnel in China [32, 33, 40]. Table 1 gives an overview of famous tunnels around the world where large fracture deformations are well controlled by the application of ductile linings [18, 25, 30-33, 37-43]. Many international conferences, including the World Tunnel Congress [18,27,44-46] and the International Rock Mechanics Congress [16,36,47-51], have paid much attention to the design and use of ductile linings in squeeze rock tunnels. It's been broken and many other conferences [42, 52-55]. In addition, many researchers have studied the effects of a limited set of design parameters on the performance of ductile linings or the interaction between rock and linings, and their results have been published in research papers [19, 23, 25, 56-65]. announced in the form of. The use of compliance elements in shotcrete linings to control the compression set in tunnels may seem straightforward, but in practice the time-dependent curing of the shotcrete, the nonlinear mechanics of compliance elements response, and face working with time. Development of rock deformation dependent on propulsion force. Incorrect use of these elements can lead to serious errors [66, 67].

2. Primary Categories of Yielding Elements

“Over the past two decades, a series of yielding elements have been developed and improved, for instance, the FFU

*Corresponding author: rahul2975@yahoo.com

element [16], Meypo, De Co-grout, Complex [25], and Telescope yielding element [36], in order to make their mechanical performances more suitable for the deformation behaviors of shotcrete and squeezing grounds. Broadly, according to their manufacturing materials, all yielding elements available can be divided into two groups: Porous concrete-based element and steel-based element [37]. A further subclassification of steel-based element is also possible, which includes steel pipe-based element and steel plate-based element. The applications of both two types of yielding elements are shown in Figure 1, where the use of porous concrete-based elements can be seen in Figure 1a, b, steel pipe-based elements can be seen in Figure 1c–e, and steel plate-based elements can be seen in Figure 1f. In this section, the structures and mechanical properties of four yielding elements mostly used in squeezing rock tunnels are discussed in detail, including one porous concrete-based element, two steel pipe-based elements, and one steel plate-based element.”

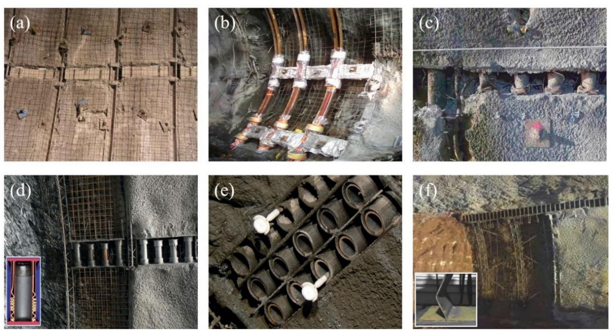

Fig. 1. Illustration for applications of yielding elements in tunnels; (a) and (b) porous concrete based element; (c–e) steel pipe-based element; and (f) steel plate-based element. Reproduced with permission from [37]

3. Highly Deformable Concrete (Hidcon) Element

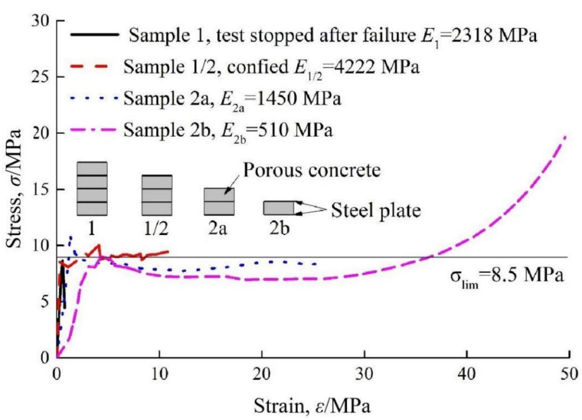

Fig. 2. Stress-strain curves for Hidcon elements applied in the Saint Martin La Porte access adit [69]. Reproduced with permission from [69]

“As shown in Figures 2a and 2b, Hidcon elements typically consist of a porous concrete matrix [24]. Tunnel engineers sometimes call this a "porous concrete element". When HICON elements are selected as the compliant element for shotcrete linings, other additives are often added to improve the compressive strength and deformability of HICON elements [68]. Saint-Martin Access Tunnel La Porte of the Lyon-Turin Base Tunnel [69]. Steel fibers have been added to greatly increase the strength of the elements. Additionally, hollow glass particles increased the controlled compression value of the element

4. Lining Stress Controller Element

“As already mentioned, the Gargenberg Tunnel in Austria was the first place where groups of axially loaded steel pipes were used as compliant elements in shotcrete linings [30]. had a series of drillings to reduce the initial stiffness due to the low strength of the new shotcrete. Buckling of the steel pipes caused such flexible elements to exhibit rather unstable load-displacement behavior. The lab's tunnel engineers are working to resolve this issue. In a tunnel construction project at the Graz University of Technology in Austria, an attempt was made to shorten the guide pipe and move it inside the steel pipe to improve the buckling path of the pipe parts [37], or “lining stress controller (LSC). Up to this point, a reliable liner load controller was axially loaded, with additional tubes simultaneously inserted at both ends of the element and concentrically aligned with the load-bearing tubes, as shown in Fig. 2d. It consisted of steel pipes [24]. These concentrically inserted additional guide tubes greatly limit the folds of the load-bearing tubes from growing inwards or outwards. As a result, the pad tension controller can better match the force and displacement behavior to the buckling strength development of a logically symmetric cylinder.

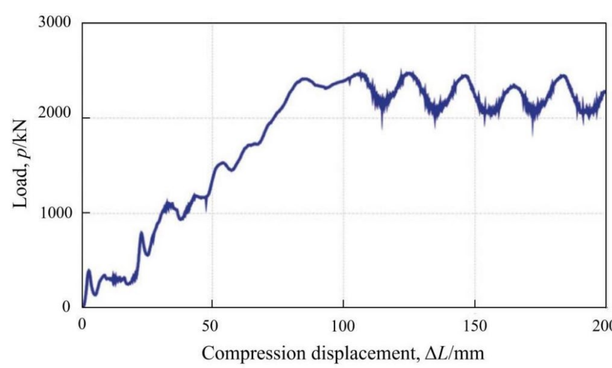

Fig. 3. Load-displacement curve for a LSC element [37]. Reproduced with permission from [37]

5. Wabe Element

“Comparing with the LSC element, the honeycomb element is an assembly of laterally loaded steel tubes connected by steel plates and finally by plates at the top and bottom, as seen in Figure 2e. Honeycomb elements were first introduced and used in the second tube of the Tauern Tunnel [38]. The load-displacement curves in Fig. 5 consist of three rows of five steel tubes each. It can be seen that the preload strength of the honeycomb element increases significantly even with a very small shortening of about 8 mm, whereas for the LSC element this value is about 80 mm. According to a, a load-bearing capacity of about 500 kN can be achieved. 30mm shorter, increased by about 200kN, final load is approx. 1400 kN thereby. The results in Figures 4 and 5 show that the constrained orientation of the steel has a significant effect on the strength of tubular steel-based members.”.

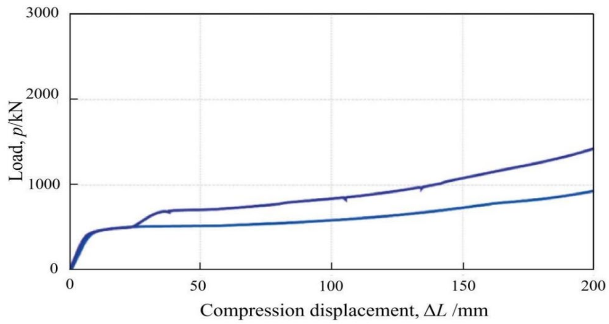

Fig. 4. Load-displacement curve for a Wabe element [37]. Reproduced with permission from [37]

One type of steel is called a Support Resistance Limiting Damper (SRLD) as shown in Figure 2f. Compliant panel elements. This component consists of a number of vertical forces limiting plates, upper and lower connecting steel plates, etc. [32, 33, 40]. The lower and upper vertical resistance limiting plates are welded to parallel connecting plates made of steel. Low carbon steel is used for the production of the vertical steel plates to ensure yield formability and Good residual intensity after peak. By utilizing the bending plastic deformation of these vertical steel plates, the drag limiting element can achieve the goal of releasing the rock deformation energy and relieving the residual stress of the shotcrete shell. A major advantage of drag-limiting materials is reportedly that they can be used in practical engineering.

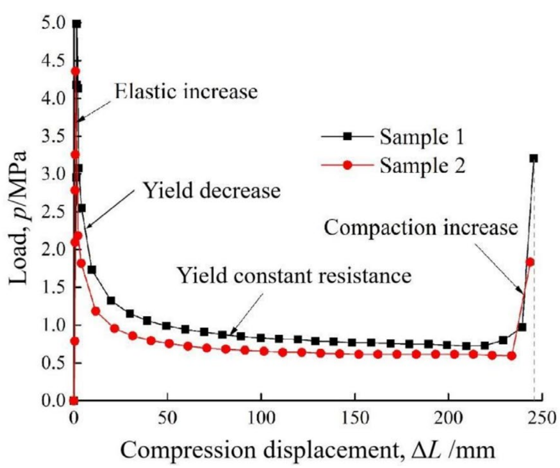

Fig. 5. Displacement-load curve for the resistance limiting element [32]. Reproduced with permission from [37]

Table 1

Criterion	HidCon	LSC	Wabe	SRLD
Deformability	Medium	High	High	High
Initial stiffness	High	Medium	Low	High
Yield stress	Medium	High	Low	Low
Installation procedure	Medium	Medium	Medium	Simple
Serviceability	Difficult	Difficult	Difficult	Difficult
Costs	Low	Low	Medium	Low

Use of yielding support is advised when tunneling through squeezing rock. The shotcrete liner is frequently divided into several segments and installed in the yielding supports with the yielding elements in between. Compared to shotcrete, the yielding element has a much greater capacity for deformation, and its yield stress can be altered to meet the demands of the supporting structure. Based on numerical analyses were carried out to examine the impact of the yield stress of the yielding element on the behaviors of the shotcrete liner. A connector element that can simulate the large deformation capability of the yielding element was used in each of these numerical analyses. The numerical findings show that the yield stress of the yielding element has a substantial demand. The review starts out by briefly introducing the background of supporting evidence and prior research work and outlining the significance of looking into this matter. Saki Kurokawa [16] concentrated on a new glass fiber reinforced plastic substance that is currently used to replace actual wood. Furthermore, uniaxial compression tests were used to assess its mechanical characteristics and deformability. The test's outcome demonstrates proper deformability and the absence of brittle failure. As a next step, the numerical analysis of the shotcrete lining model with the new deformable elements was carried out to further investigate its applicability to the yielding support element. Due to the benefit of using numerical simulation, we discovered that the stress generated in the shotcrete lining was reduced.

6. Conclusion

“Significant distortions are common during the construction of tunnels in fragile rock formations and when there is a large amount of overlying material. To prevent the support from being overloaded, multiple supple support systems have been created over the past 15 years to enable the gradual accumulation of pressure in the lining. Developing a supple support system necessitates analyzing the progression of shifts over time and space, the time-sensitive qualities of the shotcrete, and the properties of the pliable components. The characteristics of a system that can yield are outlined. The most recent advancements in pliable components that are compatible with shotcrete support are examined, and their overall effectiveness and success are clarified".

References

[1] Tran-Manh, H.; Sulem, J.; Subrin, D. Progressive degradation of rock properties and time-dependent behavior of deep tunnels. Acta Geotech. 2016, 11, 693–711.

[2] Vrakas, A.; Anagnostou, G. Ground Response to Tunnel Re-profiling Under Heavily Squeezing Conditions. Rock Mech. Rock Eng. 2016, 49, 2753–2762.

[3] Wu, K.; Shao, Z.; Qin, S.; Li, B. Determination of Deformation Mechanism and Countermeasures in Silty Clay Tunnel. J. Perform. Constr. Facil.2020, 34, 04019095.

[4] Iasiello, C.; Torralbo, J.C.G.; Fernández, C.T. Large deformations in deep tunnels excavated in weak rocks: Study on Y-Basque high-speed railway tunnels in northern Spain. Undergr. Space 2021, 6, 636– 649.

[5] Xu, C.; Xia, C. A new large strain approach for predicting tunnel deformation in strain-softening rock mass based on the generalized Zhang-Zhu strength criterion. Int. J. Rock Mech. Min. Sci. 2021, 143, 104786.

[6] Chu, Z.; Wu, Z.; Liu, Q.; Liu, B.; Sun, J. Analytical Solution for Lined Circular Tunnels in Deep Viscoelastic Burgers Rock Considering the Longitudinal Discontinuous Excavation and Sequential Installation of Liners. J. Eng. Mech. 2021, 147, 04021009.

[7] Nistor, M.M.; Rahardjo, H.; Satyanaga, A.; Hao, K.Z.; Xiaosheng, Q.; Sham, A.W.L. Investigation of groundwater table distribution using borehole piezometer data interpolation: Case study of Singapore. Eng. Geol. 2020, 271, 105590.
[8] Kontogianni, V.; Psimoulis, P.; Stiros, S. What is the contribution of time-dependent deformation in tunnel convergence? Eng. Geol. 2006, 82, 264–267.
[9] Paraskevopoulou, C.; Diederichs, M. Analysis of time-dependent deformation in tunnels using the Convergence-Confinement Method. Tunn. Undergr. Space Technol. 2018, 71, 62–80.
[10] Zhang, C.; Cui, G.; Zhang, Y.; Zhou, H.; Liu, N.; Huang, S. Squeezing deformation control during bench excavation for the Jinping deep soft-rock tunnel. Eng. Fail. Anal. 2020, 116, 104761.
[11] Wu, K.; Shao, Z.; Qin, S.; Zhao, N.; Chu, Z. An Improved Nonlinear Creep Model for Rock Applied to Tunnel Displacement Prediction. Int. J. Appl. Mech. 2021, 13, 2150094.
[12] Arora, K.; Gutierrez, M.; Hedayat, A.; Cruz, E.C. Time-Dependent Behavior of the Tunnels in Squeezing Ground: An Experimental Study. Rock Mech. Rock Eng. 2021, 54, 1755–1777.
[13] Chu, Z.; Wu, Z.; Wang, Z.; Weng, L.; Liu, Q.; Fan, L. Micro-mechanism of brittle creep in saturated sandstone and its mechanical behavior after creep damage. Int. J. Rock Mech Min. Sci. 2021, 149, 104994.
[14] Hu, B.; Sharifzadeh, M.; Feng, X.-T.; Guo, W.; Talebi, R. Role of stress, slenderness and foliation on large anisotropic deformations at deep underground excavations. Int. J. Min. Sci. Technol. 2021, 31, 577–590.
[15] Zhao, N.; Shao, Z.; Wu, K.; Chu, Z.; Qin, S. Time-Dependent Solutions for Lined Circular Tunnels Considering Rockbolts Reinforcement and Face Advancement Effects. Int. J. Géoméch. 2021, 21, 04021179.
[16] Kurokawa, S.; Masumoto, K.; Koizumi, Y.; Okada, Y.; Utsuno, M. Evaluation of deformable support in squeezing ground by experiment and numerical analysis. In Proceedings of the 5th ISRM Young Scholars' Symposium on Rock Mechanics and International Symposium on Rock Engineering for Innovative Future, Okinawa, Japan, 1–4 December 2019.
[17] Wu, K.; Shao, Z.; Sharifzadeh, M.; Chu, Z.; Qin, S. Analytical Approach to Estimating the Influence of Shotcrete Hardening Property on Tunnel Response. J. Eng. Mech. 2022, 148, 04021127.
[18] Kovári, K. Design methods with yielding support in squeezing and swelling rocks. In Proceedings of the World Tunnel Congress, Budapest, Hungary, 23–28 May 2009.
[19] Schubert, W. Dealing with squeezing conditions in Alpine tunnels. Rock Mech. Rock Eng. 1996, 29, 145–153.
[20] Ortlepp, W.; Stacey, T. Performance of tunnel support under large deformation static and dynamic loading. Tunn. Undergr. Space Technol. 1998, 13, 15–21.
[21] Öge, I.F. Revisiting the assessment of squeezing condition and energy absorption of flexible supports: A mine development case. Tunn. Undergr. Space Technol. 2021, 108, 103712.
[22] Wu, K.; Shao, Z. Study on the Effect of Flexible Layer on Support Structures of Tunnel Excavated in Viscoelastic Rocks. J. Eng. Mech. 2019, 145, 04019077.
[23] Lackner, R.; Macht, J.; Hellmich, C.; Mang, H.A. Hybrid Method for Analysis of Segmented Shotcrete Tunnel Linings. J. Geotech. Geo environmental Eng. 2002, 128, 298–308.
[24] Radonˇci´c, N.; Schubert, W.; Moritz, B. Ductile support design. Géoméch. Und Tunn. 2009, 2, 561–577.
[25] Mezger, F.; Ramoni, M.; Anagnostou, G. Options for deformable segmental lining systems for tunnelling in squeezing rock. Tunn. Undergr. Space Technol. 2018, 76, 64–75.
[26] Wu, K.; Shao, Z.; Qin, S.; Zhao, N. Mechanical analysis of tunnels supported by yieldable steel ribs in rheological rocks. Geomech. Eng. 2019, 19, 61–70.
[27] Hammer, A.L.; Thewes, M. Integration of yielding elements in various computational methods for calculations in different planning and construction phases. In Proceedings of the ITA-AITES World Tunnel Congress, Dubai, United Arab Emirates, 21–26 April 2018.
[28] Ghorbani, M.; Shahriar, K.; Sharifzadeh, M.; Masoudi, R. A critical review on the developments of rock support systems in high stress ground conditions. Int. J. Min. Sci. Technol.2020, 30, 555–572.
[29] Fan, S.; Song, Z.; Xu, T.; Wang, K.; Zhang, Y. Tunnel deformation and stress response under the bilateral foundation pit construction: A case study. Arch. Civ. Mech. Eng. 2021, 21,109.
[30] Schubert, W.; Brunnegger, S.; Staudacher, R.; Wenger, J. Further development of yielding elements and connecting elements for shotcrete. Géoméch. Und Tunn. 2018, 11, 575–581.
[31] Barla, G.; Bonini, M.; Semeraro, M. Analysis of the behaviour of a yield-control support system in squeezing rock. Tunn. Undergr. Space Technol. 2011, 26, 146–154.
[32] Qiu, W.; Wang, G.; Gong, L.; Shen, Z.; Li, C.; Dang, J. Research and application of resistance-limiting and energy-dissipating support in large deformation tunnel. Chin. J. Rock Mech. Eng. 2018, 37, 1785–1795.
[33] Deng, Y.; Xie, J.; Li, S. Research and Application of Support Resistant Limiting Dampers in the Deep-Buried Large-Section Loess Tunnel. Adv. Civ. Eng. 2020, 2020, 8841703.
[34] Entfellner, M.; Hamdi, P.; Wang, X.; Wannenmacher, H.; Amann, F. Temporary Removal: Investigating High-Strength Expanded Polystyrene (HS-EPS) as yielding support elements for tunnelling in squeezing ground conditions. Tunn. Undergr. Space Technol. 2021, 118, 104186.
[35] Wu, K.; Shao, Z.; Qin, S.; Wei, W.; Chu, Z. A critical review on the performance of yielding supports in squeezing tunnels. Tunn. Undergr. Space Technol. 2021, 115, 103815.
[36] Verient, M.; Kluckner, A.; Radoncic, N.; Schubert, W. Investigations on telescope yielding elements with porous filling. In Proceedings of the ISRM Regional Symposium-EUROCK, Salzburg, Austria, 7– 10 October 2015.
[37] Moritz, B. Yielding elements—Requirements, overview and comparison/Stauchelemente—Anforderungen, Überblick und Vergleich. Géoméch. Und Tunn. 2011, 4, 221–236.
[38] Weidinger, F.; Lauffer, H. The Tauern tunnel first and second tubes from the contractor's viewpoint. Géoméch. Und Tunn. 2009, 2, 24–32.
[39] Bonini, M.; Barla, G. The Saint Martin La Porte access adit (Lyon–Turin Base Tunnel) revisited. Tunn. Undergr. Space Technol. 2012, 30, 3854.
[40] Li, C.; Wang, G.; Qiu, W.; Gong, L.; Zhao, Y.; Wang, Q. Research and application of support resistant limiting dampers in the tunnel with high horizontal geostress. Mod. Tunn. Tech. 2020, 57, 15–24.
[41] Moritz, B. Ductile Support System for Tunnels in Squeezing Rock. Ph.D. Thesis, Graz University of Technology, Graz, Austria, 1999.
[42] Kolymbas, D. Stress and deformation fields around a deep circular tunnel. In Tunnelling and Tunnel Mechanics: A Rational Approach to Tunnelling; Springer: Berlin/Heidelberg, Germany, 2005; pp. 273–306.
[43] Merlini, D.; Stocker, D.; Falanesca, M.; Schuerch, R. The Ceneri Base Tunnel: Construction Experience with the Southern Portion of the Flat Railway Line Crossing the Swiss Alps. Engineering 2018, 4, 235–248.
[44] Bhavsar, H.; Dinis, A.; Fernandes, E.M.; Antunes, P.; Melâneo, F. Design and construction of tunnels in zones subjected to high convergences. In Proceedings of the World Tunnel Congress, São Paulo, Brazil, 9–14 May 2014.
[45] Schubert, W.; Brunnegger, S. New ductile tunnel lining system. In Proceedings of the World Tunnel Congress, Bergen, Norway, 9–15 June 2017.
[46] Hasanpour, R.; Hammer, A.L.; Thewes, M. Analysis of multilateral interaction between shotcrete, yielding support and squeezing ground by means of two different numerical methods. In Proceedings of the ITA-AITES World Tunnel Congress, Dubai, United Arab Emirates, 21–25 April 2018.
[47] Button, E.A.; Schubert, W.; Moritz, B. The application of ductile support methods in Alpine tunnels. In Proceedings of the 10th ISRM Congress, Sandton, South Africa, 8–12 September 2003.
[48] Anagnostou, G.; Cantieni, L. Design and analysis of yielding support in squeezing ground. In Proceedings of the 11th ISRM Congress, Lisbon, Portugal, 9–13 July 2007.
[49] Radoncic, N.; Schubert, W. Calculation of the shotcrete utilization for lining with integrated yielding elements. In Proceedings of the ISRM International Symposium on Rock Mechanics-SINOROCK 2009, Hong Kong, China, 1922 May 2009.
[50] Radoncic, N.; Schubert, W. System behaviour in weak ground: Comparison of yielding elements. In Proceedings of the 12th ISRM Congress, Beijing, China, 16–21 October 2011.
[51] Li, C.C. Development trend of underground rock support. In Proceedings of the 13th ISRM Congress, Montreal, QC, Canada, 10–13 May 2015.
[52] Thut, A.; Naterop, D.; Steiner, P.; Stolz, M. Tunnelling in squeezing rock-yielding elements and face control. In Proceedings of the 8th International Symposium on Tunnel Construction and Underground Structures, Lubljana, Slovenia, 15–30 October 2006.
[53] Schubert, W. Design of ductile tunnel linings. In Proceedings of the 42nd US Rock Mechanics Symposium (USRMS), San Francisco, CA, USA, 29 June–2 July 2008.
[54] Hammer, A.L.; Hasanpour, R.; Hoffmann, C.; Thewes, M. Numerical analysis of interaction behavior of yielding supports in squeezing ground.

In Proceedings of the 9th European Conference on Numerical Methods in Geotechnical Engineering, Porto, Portugal, 25–27 June 2018.
[55] Schubert, W.; Radoncic, N. Tunnelling in "Squeezing" ground conditions-problems and solutions. In Proceedings of the 13th ISRM International Congress of Rock Mechanics, Montreal, QC, Canada, 10–13 May 2015.
[56] Ramoni, M.; Anagnostou, G. The Interaction Between Shield, Ground and Tunnel Support in TBM Tunnelling Through Squeezing Ground. Rock Mech. Rock Eng. 2010.
[57] Tian, H.; Chen, W.; Yang, D.; Wu, G.; Tan, X. Numerical analysis on the interaction of shotcrete liner with rock for yielding supports. Tunn. Undergr. Space Technol. 2016, 54, 20–28.
[58] Tian, H.; Chen, W.; Tan, X.; Yang, D.; Wu, G.; Yu, J. Numerical investigation of the influence of the yield stress of the yielding element on the behaviour of the shotcrete liner for yielding support. Tunn. Undergr. Space Technol. 2018, 73, 179–186.
[59] Radonˇci´c, N.; Schubert, W. Novel method for ductile lining pre-design. Geomech. Tunn. 2011, 4, 195–210.
[60] Wu, K.; Shao, Z.; Qin, S.; Zhao, N.; Hu, H. Analytical-based assessment of effect of highly deformable elements on tunnel lining within viscoelastic rocks. Int. J. Appl. Mech. 2020, 12, 2050030.
[61] Cantieni, L.; Anagnostou, G. The interaction between yielding supports and squeezing ground. Tunn. Undergr. Space Technol. 2009, 24, 309–322.
[62] Lei, S.X.; Zhao, W. Study on the mechanism of circumferential yielding support for soft rock tunnel with large deformation. Rock Soil Mech. 2020, 41, 1039–1047.
[63] Wu, K.; Shao, Z.; Qin, S. An analytical design method for ductile support structures in squeezing tunnels. Arch. Civ. Mech. Eng. 2020, 20, 1–13.
[64] Gschwandtner, G.G.; Galler, R. Input to the application of the convergence confinement method with time-dependent material behaviour of the support. Tunn. Undergr. Space Technol. 2012, 27, 13–22.
[65] Fan, S.; Song, Z.; Xu, T.; Zhang, Y. Investigation of the microstructure damage and mechanical properties evolution of limestone subjected to high-pressure water. Constr. Build. Mater. 2021, 316, 125871.
[66] Asef, M.; Reddish, D.; Lloyd, P. Rock–support interaction analysis based on numerical modelling. Geotech. Geol. Eng. 2000, 18, 23–37.
[67] Sun, Y.; Bi, R.; Chang, Q.; Taherdangkoo, R.; Zhang, J.; Sun, J.; Huang, J.; Li, G. Stability Analysis of Roadway Groups under Multi-Mining Disturbances. Appl. Sci. 2021, 11, 7953.
[68] Chu, Z.; Wu, Z.; Liu, B.; Liu, Q. Coupled analytical solutions for deep-buried circular lined tunnels considering tunnel face advancement and soft rock rheology effects. Tunn. Undergr. Space Technol. 2019, 94, 103111.
[69] Wu, K.; Shao, Z.; Qin, S. A solution for squeezing deformation control in tunnels using foamed concrete: A review. Constr. Build. Mater. 2020, 257, 119539.