



关于高地应力软弱围岩大变形问题的哲学思考

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摘要: 随着线路等级的提高, 隧道必然朝着“深、长、大”方向发展, 而“深、长、大”的特点显著增加了发生高地应力软弱围岩大变形的风险。20 世纪初发生首例软岩大变形以来, 该问题一直是困扰隧道工程设计施工的难题。本文运用辩证思维对软弱围岩大变形问题进行哲学反思, 并提出解决问题的新思路。首先, 运用矛盾分析法分析了大变形的本质。其次, 从现实性与可能性, 内因与外因的辩证关系, 分析了大变形的预测问题, 探讨了矿山法隧道支护理念与技术的演化规律。最后, 基于对大变形支护理念的反思, 提出: 一般大变形应坚持调动围岩这个内因, 采用“抗”的理念进行支护; 严重大变形应坚持采用“抗放结合”理念下的让压支护设计。

关键词: 高地应力; 软弱围岩; 大变形; 哲学思考

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引言

随着线路等级的提高, 隧道必然朝着“深、长、大”方向发展, 而“深、长、大”的特点显著增加了发生高地应力软弱围岩大变形的风险。这类变形呈现出速率快、量级大、持续时间长、难控制等特点, 往往因初期支护破坏侵限而反复被拆换, 给工程的安全、成本、进度等带来严重挑战。20 世纪初国外发生首例软岩大变形以来, 该问题便一直是困扰隧道工程设计施工的难题^[1-18]。隧道科技工作者一般采用科

学的逻辑思维方法从以下 6 个方面对该问题开展研究: (1) 软岩大变形机制; (2) 软岩大变形分级; (3) 预测体系; (4) 大变形控制技术; (5) 支护类型的选择; (6) 围岩变形规律。

哲学反思是不断追问事物本质的思维方式, 其典型代表是辩证思维。唯物辩证法的范畴、观点、规律在思维中的运用即辩证思维, 辩证思维与“非此即彼”的逻辑思维相得益彰。马时强^[19]针对修建隧道及地下工程面对的围岩和地下水这两个对象, 对“放”与“抗”、“排”与“堵”两种处治理念进行了

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哲学反思, 研究发现是“抗”还是“放”应坚持从围岩或地下水本身这个内因出发, 在考虑需求者主体的价值取向条件下, 善于抓住主要矛盾, 努力寻求“抗”“放”这对矛盾体的统一面, 进而得到最优方案。而在后续的研究中, 马时强^[20]针对隧道工程建设面临的围岩稳定、地下水、开挖方法与支护形式三个重大问题, 进行了辩证思考。上述文献将哲学反思用于指导解决隧道工程具有普遍意义的重大问题, 但目前尚无对软弱围岩大变形问题进行哲学反思的报道。本文将从大变形的本质、预测、支护理念与技术方面对软弱围岩大变形问题进行哲学反思, 为处治高地应力软弱围岩大变形问题提供新的视角, 提升处理该问题的智慧和艺术。

1 大变形的本质

变形是应变的宏观表现, 应变是应力和模量这对主要矛盾作用的结果。围岩变形的本质可表述为地应力因开挖、支护作用而重新分布后与围岩模量这对矛盾相互作用后的宏观现象。而这种宏观现象往往又与围岩的强度、泊松比、黏性系数等参数相关, 表现为弹性、塑性和黏性等特征。因此, 变形的内因是地应力, 内因是围岩的物理力学参数。显然, 高地应力软岩就容易发生因围岩自身变形引起的具有显著时间效应的洞壁大位移。这种洞壁大位移表现为开裂、起皮、扭曲等。而这些现象也可能是因为围岩坍塌、岩块沿结构面的整体裂化所致。因此, 深入认识围岩大变形必须与洞壁大位移、围岩变形大这两个概念作严格区分。变形一定伴随位移, 但位移不一定包含变形。因此, 洞壁大位移不一定包含围岩变形, 在低应力条件下岩块沿结构面滑动也可发生大位移。本文讨论的围岩大变形特指高地应力条件下软弱围岩大量级变形, 这种变形具有显著的时间效应, 是各处围岩变形的累积结果; 而单纯的围岩变形大是指隧道开挖后在较大的二次应力作用下, 当围岩强度较低、模量较小时围岩发生的较大变形, 这类变形不具有显著的时间效应。因此, 围岩变形大和洞壁大位移均不能等同于围岩大变形。

国际岩石力学学会将高地应力软岩大变形称为

“挤压型变形”, 其发生的外因是高地应力, 内因是围岩本身低强度、低模量、高流变属性。发生机理是岩体内的剪应力超过抗剪强度而引起的剪切蠕动, 这种蠕动使得松动区与塑性区不断向深部扩展。这才是围岩大变形固有的内部联系, 也即哲学范畴的本质。

2 大变形的预测

对围岩大变形的预测应首先着眼于围岩本身这个内因。因为内因是事物发展变化的根据, 它规定了事物发展的基本趋势和方向。针对围岩这个内因, 不仅从围岩强度来评价软岩, 还要重视岩石种类、岩性及结构条件。例如探明千枚岩、片岩、板岩、页岩、断层带等典型软弱或破碎并具有显著的各向异性, 层薄质软的岩石在同等外部条件下的变形特性。根据塑性区洞周位移公式计算可知, 变形模量和内摩擦角是大变形的高敏内因^[21]。外因是事物发展的必要条件, 是事物发展的第二位原因, 需要通过内因对事物发展起加速或延缓作用。围岩所处的外部环境就是其外因, 主要是地应力场、地质构造、地下水、工程因素等。它对大变形的发展起着加速或延缓的作用。大变形的预测就是在开挖前对围岩挤出程度给出量化的分级标准。目前, 学者提出的分级标准均综合内外因两方面指标给出了判据, 既有单一指标判据, 也有综合指标判据。包括采用岩石单轴抗压强度与上覆地层重力的比值作为预测指标^[22]; 采用岩体单轴抗压强度与上覆地层重力的比值作为预测指标^[23]; 采用隧道相对位移与岩体强度应力比相结合作为预测指标^[24]; 采用基于地层 Q 值的“临界埋深法”^[25]。其中临界埋深值是岩体质量系数 Q 的函数, 《铁路隧道设计规范》(TB10003—2016) 建议以岩石单轴抗压强度与最大地应力之比作为预测指标, 采用围岩力学参数和地应力作为预测指标^[26]。内外因方法论要求在观察事物、分析问题时, 坚持内外因相结合的观点。对内因要给予充分重视, 对外因根据利弊作“一分为二”的分析。过去常用围岩强度应力比这个相对指标作为大变形基本判据, 由于地应力绝对值反映了围岩变形能量的大小, 岩体的变形模量及内摩擦角是围岩变形

的主要内因,且各影响因素对大变形的敏感程度不一。因此,应对各影响因素进行权重分配,构造判断矩阵,进一步得到各影响因素的权重集。预测是基于现有信息,依照一定的方法和规律对事情未来进行测算,预先了解其发展的过程与结果。哲学层面的预测是对现实性与可能性辩证关系的把握,而可能性总是潜伏在现实事物之中,精准地判断可能性,取决于对现实性的全面把握。在对围岩大变形进行预测时,在不同阶段对引起变形的内外因的把握程度是不同的。因此,可根据获取的地质勘查资料,基于地应力场类型、地层岩性和地质构造,首先判断是否应当进行大变形预测,然后根据设计阶段勘察资料进行大变形初判,施工阶段根据揭露的更加详细的内外因资料做出大变形详判^[27]。

3 大变形的支护理念与支护技术

3.1 矿山法隧道支护理念与技术的演化规律

矿山法隧道修建方法主要包括传统矿山法、新奥法、挪威法、新意法、浅埋暗挖法等。传统矿山法的基本理念是坍塌形成的天然“卸载拱”承担上部围岩压力,支撑结构被动承担“卸载拱”以下坍塌岩体的自重。其技术背景为木排架、钢架等传统支护手段和分部开挖法。支撑顶替和开挖作业反复扰动围岩,坍塌高度是设计的重点,支撑结构是隧道稳定的关键。新奥法的基本理念是充分调动并利用围岩的承载能力。被动的“支撑”转变为主动的“支护”,支护的目的是改造和利用围岩,让支护与围岩合二为一。相应的技术背景为通过采用控制爆破技术来减少对围岩的扰动,通过采用锚喷支护技术来加固和适应围岩的变形,以发挥围岩的承载能力,通过监控量测技术来评估支护与围岩的受力状态。挪威法的基本理念是采用高性能的锚喷支护来加固和利用围岩承载力,尽量避免采用被动支撑的二次衬砌。相应的技术背景为高质量的湿喷钢纤维混凝土和全长胶结型高拉力耐腐蚀的锚杆形成的能适应较大变形的高性能锚喷支护。新意法的基本理念是通过加固掌子面前方围岩,提高其刚度,以控制掌子面前方围岩的预收敛变形,实现全

断面开挖,进而减少对围岩的开挖扰动次数,实现围岩变形控制。相应的技术背景包括玻璃纤维锚杆在内的掌子面前方围岩加固和监控量测技术。浅埋暗挖法的基本理念是综合运用多种辅助工法,超前支护,改善加固围岩,调动部分围岩自承载能力,尽量增大支护的承载,减少围岩的自承载^[28]。相应的技术背景是分部开挖、超前锚杆或超前小导管、深孔注浆加固地层、长管棚超前支护、地层冻结法、水平旋喷超前支护等辅助施工措施。

围岩及加固围岩的主动支护是隧道稳定的内因,被动的支撑是外因。在分析围岩支护理念及技术时,应坚持内外因相结合,充分重视内因对围岩稳定的作用,对外因要结合实际充分辨析其利弊,进行“一分为二”的分析。传统矿山法一律采用被动支撑抵抗松散压力,不注重内因的挖掘,显然是过时的理念。新奥法核心理念是改造和利用围岩,发挥围岩的承载能力,让支护结构与围岩密贴,以达到合二为一,这是充分重视内因的表现。二次衬砌属于外因,需分析其利弊后合理应用。这就要求围岩和初期支护基本稳定后施作二次衬砌,过早施作将限制围岩和初期支护的有利变形,导致二次衬砌过度受力。挪威法更加重视内因的作用,采用高质量的支护结构去改造围岩,让围岩和锚喷支护承载,除特殊情况外一般不采用二次衬砌。新意法从尽早控制围岩变形的角度,把重点放到掌子面前方围岩的挤出变形控制上,再通过全断面开挖减少扰动,尽可能维持围岩的初始状态,进而提高围岩的承载能力,显然也是更加重视内因作用的表现。根据唯物辩证法观点,内因和外因在一定条件下是可以互相转化的。当隧道埋深很浅,或者围岩特别软弱时,均很难通过加固围岩来实现围岩承载,此时支护结构才是确保围岩稳定的内因,围岩很大程度上已经是荷载,并作为不利于隧道稳定的外因而存在,应该设法让这种荷载更有利于支护结构稳定。浅埋暗挖法正是在新奥法理念上,针对浅埋和软岩,在内因和外因的方法论指导下做出的支护理念调整。这也体现了唯物辩证法运用联系和发展的观点处理问题的智慧和艺术。这种处理问题的智慧和艺术也将应用到大变形的支护理念中。

黑格尔 (Georg Wilhelm Friedrich Hegel) 指出^[29], 哲学的任务就是要跟随在人类知识后面, 进行反复思考, 把握人类知识的辩证的历史发展。通过以上分析可以得出矿山法隧道支护理念与支护技术的演化规律如下: 从一味强调被动支护结构这个外因, 到不断重视围岩这个内因的作用, 再到坚持内外因相结合, 并能灵活把握内外因双方力量此消彼长而互换其位, 当外因的力量大于内因时, 外因就起决定作用, 反之亦然。以上认识规律也正好符合当今学者对内因和外因关系的再认识^[30-31]。

3.2 大变形的支护理念与技术的反思

探讨大变形的支护理念与技术, 本质上是对解决大变形问题方法的反思, 而矛盾构成了方法的内在本性。下面将运用矛盾的观点并在由此引出的辩证法“三大规律”“五对范畴”框架下, 对大变形的支护理念和技术进行反思。

基于对围岩大变形本质的认识, 从现实性与可能性、内因与外因的范畴对围岩大变形的发生和发展作出预测, 是处理大变形问题的逻辑起点。处理大变形的核心理念无非是“抗”“放”和“抗放结合”。根据大变形的分级预测结果选择处治理念。大变形可分为一般大变形和严重大变形, 或称为收敛型大变形和不收敛型大变形^[32]。其本质区别在于, 一般大变形其塑性区虽不断向深部发展, 但最终在无支护作用条件下能够自稳, 尽管此时的洞周围岩变形已超过正常预留值。严重大变形其塑性区不断向深部发展, 且在无支护作用条件下最终变形不收敛。针对一般大变形应通过及时支护、强支护体现“抗”的理念。针对严重大变形应通过超前导洞、让压支护结构等措施体现“放”的理念, 但这种“放”是为了更好地“抗”, 因此本质上是“抗放结合”的理念。下面详细论述两类大变形的支护理念与技术。

针对一般大变形, 应始终强调围岩作为内因的根本作用。体现在始终致力于保护, 及早加固围岩并最终利用围岩和初期支护共同承担围岩压力, 控制围岩变形。围岩加固以掌子面前方 0.5 倍开挖洞径范围为主, 掌子面后方围岩为辅。初期支护务必与围岩密贴, 体现支护结构与围岩合二为一, 避免支护结构受

弯破坏。通过锚杆加固掌子面, 采用全断面一次开挖, 减少对围岩的扰动。增加锚杆长度、提高混凝土适应变形的能力、优化洞形、尽早封闭成环。这里强调的“抗”主要是通过主动加固围岩, 让围岩来抵抗围岩压力。型钢拱架、预应力锚索这种刚性的被动支护结构可在确保预留量的前提下, 用于二次补强, 体现支护结构“抗”的理念。

针对严重大变形, 应坚持内外因相结合, 并灵活把握内外因的转化。当地应力过大时, 单纯依靠加固围岩已不能控制大变形的发展。此时应在加固围岩的同时致力于降低地应力水平。地应力在开挖前以应变能的形式存在于岩体之中, 开挖后存储的能量将以对外做功的形式得以释放。假设支护抗力一定, 那么变形越大则说明围岩中蓄积的能量越大。如何在可控制的变形尺度下大幅释放围岩中蓄积的能量呢? 物理学中规定, 功等于力与物体在力的方向上移动的距离。显然, 为了有效控制变形, 可以提高支护抗力并允许围岩及支护结构在抗力反方向有较大的变形。以上就是让压设计理念的本质, 也是“抗放结合”理念的精髓。根据以上理念发明的大变形治理技术包括: 先行导坑应力释放法、恒阻大变形锚索支护技术、恒阻可缩性钢拱架支护技术等^[33]。以上支护技术的共同点是支护结构保持一定阻力情况下能产生较大变形, 使蓄积较大应变能的围岩以对外做功的形式将能量释放。此外, 处理大变形隧道不得不采用的反复扩挖更换初期支护的技术, 实际上也是让能量不断释放, 最后在常规支护结构下实现围岩稳定。事物总具有两面性, 既对立又统一。“抗放结合”的让压设计在处理严重大变形问题时, 也必须注意到: 让压量越大, 围岩应变能释放越多, 围岩和支护结构承受的围岩压力就越小, 但过度释放可能导致围岩的破坏甚至塌方。应变能释放过小则达不到释放目的。因此, 释放的度以及让压结构在较大范围内实现可调可控就是值得探讨的问题。对于收敛型大变形, 当可量测洞周变形达到洞周半径的 3% 时, 支护结构的应力可减小至常规支护结构的承受范围。对于非收敛型大变形, 可量测洞周变形要达到洞周半径的 14% 时, 让压效果才明显^[34]。

“抗放结合”的让压设计理念是将主要矛盾聚焦在地应力这个外因上, 致力于合理释放高地应力引起的应变能, 但同时也不能忽视了围岩这个内因的作用。在及时主动支护下, 开挖后洞周围岩的位移及塑性区的扩展都能得到有效的控制, 进而减小作用在支护结构上的围岩压力; 也能尽快将松动圈加固为承载拱, 提高围岩的抗力, 以便与让压支护结构一起消耗应变能。

二次衬砌是稳定隧道的外因。对于外因需要辨明其积极和消极面。二次衬砌施作时机是发挥其积极面的关键, 软岩大变形条件下二次衬砌的施作时机应与支护理念结合起来整体考虑。当初期支护采用“抗”的理念进行围岩加固并提高支护抗力时, 适时提前施作二次衬砌是合理可行的, 二次衬砌与初期支护和围岩共同承载, 这与新奥法保护围岩, 充分发挥围岩自承载能力的原则是一致的^[35]。当初期支护采用“抗放结合”理念进行让压设计时, 二次衬砌可在围岩应变能释放一定程度后及时施作。

4 结论

本文在唯物辩证法的视角下对高地应力软岩大变形的本质、大变形的预测及大变形支护理念与技术进行了反思。得出以下结论。

(1) 大变形的本质是以高地应力为代表的外因与以围岩本身性质为代表的内因这一对矛盾作用下发生的因围岩自身变形引起的具有显著时间效应的洞壁大位移。

(2) 对围岩大变形的预测应坚持以围岩本身性质这个内因为主, 以地应力、地下水、地质构造等外因为辅, 并根据对内外因的把握程度, 分阶段进行预测。

(3) 矿山法隧道支护理念与技术的演化规律为从重视外因到重视内因, 再到内外因相结合, 并在一定条件下把握内外因相互转化。

(4) 一般大变形应坚持调动围岩这个内因, 采用“抗”的理念进行支护。严重大变形应坚持采用“抗放结合”理念下的让压支护设计。

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Philosophical Reflection on the Problem of Large Deformation of Weak Surrounding Rocks under High Ground Stress

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Highlights

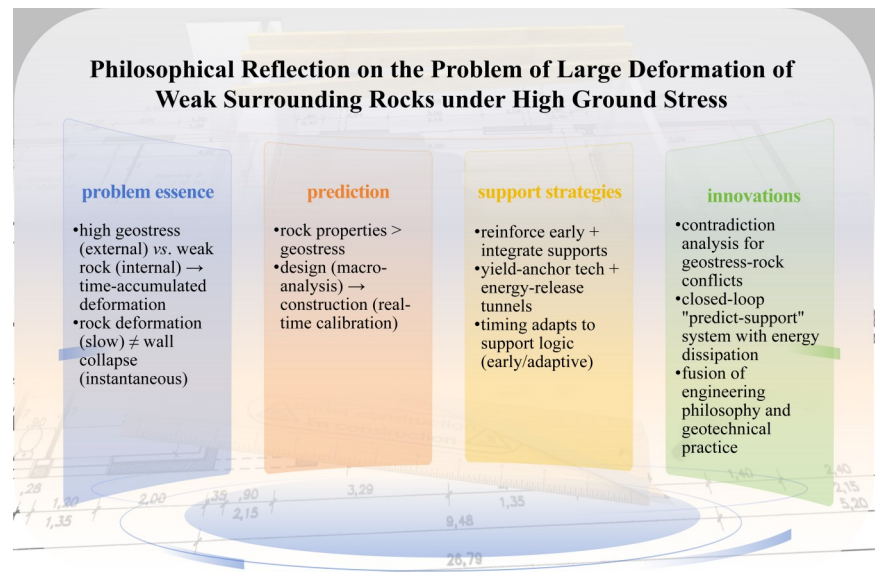
Synthesizes dialectical philosophy with engineering practice, proposing a “resistance-yield synergy” framework to transcend technical limitations.

Distinguishes “surrounding rock deformation” from “wall displacement”, reframing essence as a time-accumulated contradiction between high geostress (external) and low-strength/high-rheology rock (internal).

Traces tunneling method evolution (traditional mine—NATM—Norwegian—shallow-buried excavation), revealing a paradigm shift toward “internal-external synergy” and dynamic equilibrium between support strength and rock self-bearing capacity.

Proposes a closed-loop framework for severe deformation: “strain energy release—rock reinforcement synergy” *via* yielding structures (e.g., constant-resistance anchors), addressing extreme-condition support gaps.

Graphical Abstract



Abstract: With the improvement of the line level, tunnels will inevitably develop towards the direction of “deep, long, and large”, and the characteristics of “deep, long, and large” significantly increase the risk of large deformation of high stress weak surrounding rock. Since the first large-scale deformation of soft rock occurred in the early 20th century, this problem has been a difficult problem for tunnel engineering design and construction. Tunnel technology workers generally use scientific logical thinking methods to conduct research on this issue. This study adopts dialectical thinking to philosophically reflect on the problem of large deformation of weak surrounding rock from the aspects of the essence, prediction, support concept, and technology of large deformation. It provides a new perspective for dealing with the problem of large deformation of high stress weak surrounding rock and enhances the wisdom and art of dealing with this problem.

The International Society of Rock Mechanics refers to high stress soft rock deformation as “compression type deformation”, which occurs due to high ground stress as the external cause and low strength, low modulus, and high rheological properties of the surrounding rock as the internal cause. The mechanism of occurrence is the shear creep caused by the shear stress in the rock mass exceeding the shear strength, which continuously expands the loose zone and plastic zone to the deeper part. The essence of large deformation is the large displacement of the tunnel wall caused by the deformation of the surrounding rock itself, which occurs under the contradictory action of external factors represented by high ground stress and internal factors represented by the properties of the surrounding rock itself. This large displacement exhibits a significant time cumulative effect.

The prediction of large deformation of surrounding rock should adhere to the principle of focusing on the intrinsic properties of the surrounding rock itself, supplemented by external factors such as geostress, groundwater, and geological structure. Based on the obtained geological exploration data and the type of geostress field, formation lithology, and geological structure, the first

step is to determine whether large deformation prediction should be carried out. Then, the preliminary judgment of large deformation should be made based on the exploration data in the design stage, and the detailed judgment of large deformation should be made based on the more detailed internal and external factors revealed in the construction stage.

Hegel pointed out that the task of philosophy is to follow human knowledge, engage in repeated thinking, and grasp the dialectical historical development of human knowledge. Using the methodology of dialectical principles of internal and external factors, this study analyzes the evolution of the concept and technology of tunnel support in mining methods. It is found that from emphasizing passive support structures as the external factor, to continuously valuing the role of surrounding rock as the internal factor, to adhering to the combination of internal and external factors, and being able to flexibly balance the strengths of both parties and exchange their positions. When the strength of the external factor is greater than that of the internal factor, the external factor plays a decisive role, and vice versa. The above rules of understanding are also in line with the current scholars're understanding of the relationship between internal and external factors.

Large deformations can be divided into general large deformations and severe large deformations. The essential difference lies in the fact that although the plastic zone of large deformations continues to develop deeper, it can eventually self stabilize under unsupported conditions, even though the deformation of the surrounding rock has exceeded the normal reserved value. The plastic zone of severe large deformation continues to develop deeper, and the final deformation does not converge under unsupported conditions. For general large deformations, the fundamental role of surrounding rock as the internal cause should always be emphasized. The concept of “resistance” should be reflected through timely and strong support, which is always committed to protection, early reinforcement of surrounding rock, and ultimately using surrounding rock and initial support to jointly bear the pressure of surrounding rock and control its deformation. In response to severe and large deformations, we should adhere to the combination of internal and external factors, and flexibly grasp the transformation of internal and external factors. The concept of “release” should be reflected through measures such as advanced guide holes and pressure support structures. However, this “release” is to better “resist”, so it is essentially the concept of “combination of resistance and release”. The design concept of “combining resistance and release” focuses on the external factor of geostress as the main contradiction, aiming to reasonably release the strain energy caused by high geostress, but at the same time, the role of surrounding rock as the internal factor cannot be ignored. With timely and proactive support, the displacement of the surrounding rock and the expansion of the plastic zone can be effectively controlled after excavation, thereby reducing the surrounding rock pressure acting on the support structure; It is also possible to quickly reinforce the loose ring into a load-bearing arch, improve the resistance of the surrounding rock, and consume strain energy together with the yielding support structure.

Keywords: high ground stress; weak surrounding rock; large deformation; philosophizing