含水层结构变异对区域地下水循环影响数值模拟

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煤炭开采对地下水资源的破坏是限制煤矿区经济与环境可持续发展的主要瓶颈, 煤炭资源开采与水资源保护的矛盾将日益加剧。我国富煤地区主要分布在华北和西北, 仅山西、内蒙古、陕西和新疆四省自治区煤炭查明资源储量就占全国的 73.1%, 这些富煤地区多是地下水资源相对贫乏的地区, 全国 86 个重点矿区缺水的占 71%, 严重缺水的占 40%, 而煤矿开采对地下水资源的严重破坏加剧了矿区的水资源短缺矛盾, 这一问题在能源大省山西尤为突出。究其根本原因, 在于采煤引起含水层结构变化, 造成地下水资源的破坏, 使地下水资源由原来可供开采的优质水源变为被污染的矿坑水而排走, 破坏了地下水的补径排, 破坏了水文下垫面条件, 破坏了地表水循环, 进而影响了区域地下水循环态势。

采煤过程中, 围岩破坏使隔水层与含水层骨架发生变化, 加上矿井水的大量疏排, 导致地下水流场向采煤状态下的地下水循环模式演化。煤矿闭坑后, 已被采矿扰动了的矿区地下水流场和赋存环境再次发生变化。原已疏干的含水层及采矿扰动裂隙空间被重新充水淹没, 水化学环境也同时发生明显的变化, 形成采煤后地下水环境循环演化的新模式。这种采煤过程中和采煤后地下水循环模式的演化具有时空四维动态演化性、非线性和复杂性。以往的研究工作多是从单个煤矿采动裂隙连通的导水性和采矿突水机理的角度开展研究, 对于采动裂隙时空动态演化对含水层结构变异的影响机制, 以及从群矿采煤驱动的角度研究含水层空间结构非均质演化对区域地下水循环演化轨迹和演化趋势研究不够, 然而这是揭示采煤引起地下水资源再分布规律和阐明采煤条件下区域地下水循环演化真实模式的关键。在群矿采煤条件下, 广大区域内的地下水资源遭到破坏, 地下水环境恶化, 揭示采煤后区域水循环演化的真实规律是实现水资源的调控和优化配置技术基础, 也是实现矿区经济、资源和环境协调发展的关键问题。

本文以山西长治盆地潞安矿区为研究对象, 结合理论分析和数值模拟对群矿开采条件下含水层结构变异对区域地下水循环机制影响开展深入研究, 揭示了煤层开采后区域含水层空间结构变异规律, 查明采煤过程中和采煤后地下水资源再分布的真实状态, 进一步发展含水层空间结构变异下的地下水系统演化新理论, 并丰富变化环境下的区域水循环研究; 揭示群矿采煤驱动下地下水循环演化特征和地下水资源再分布规律, 一定程度上实现含水层空间结构变异对地下水循环演化影响机制研究的特色创新和理论突破; 本研究开展不仅对煤矿采区经济、资源和环境的可持续发展具有现实意义, 而且对群矿采煤条件下地下水循环演化领域的研究具有理论价值, 为矿区地下水资源的可持续科学利用和采煤保水规划设计提供参考依据。

1 主要研究内容

(1)采动裂隙时空演化对区域含水层结构变异影响研究。通过开展典型矿区采煤影响范围内覆岩结构变形、破坏和采动裂隙的时空分布特征及动态演化过程的研究, 取得含水介质埋藏深度、厚度、边界条件性质的变化, 含水介质孔隙和裂隙率的变化, 新含水介质的组合特征信息和数据, 阐明采煤影响范围内含水介质非均质性演化特征; 通过含水介质隔水和导水性质相互转化机制的研究, 进而揭示煤层开采引起的含水层结构变异规律, 建立典型矿区采煤影响范围含水层结构变异模型。

(2)群矿开采驱动下含水层结构变异对区域水循环影响数值模拟研究。在深入研究群矿采煤引起区域含水层空间结构非均质演化特征和演化趋势的基础上, 获取采煤后区域地下水的最新补、径、排信息和数据, 探讨区域地下水流模式在采煤过程中的变化规律, 开展群矿采煤驱动下水文地质结构演化与地下水流模式耦合效应研究, 揭示含水层空间

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结构非均质演化对区域水循环影响机制，建立群矿采煤驱动下区域地下水循环演化模式。

(3)采煤驱动下区域地下水资源演化趋势与再分布研究。利用群矿采煤驱动下区域地下水循环演化研究成果，开展采煤过程中和煤层开采后地下水资源演化趋势与再分布的研究，建立开采条件下的水资源评价模式，进行盆地范围水资源综合评价，揭示煤层开采后地下水资源重新分布后的状况、特点、变化规律和可利用程度。

2　主要研究成果

(1)基于含水介质隔水和导水性质相互转化机制研究，利用 FLAC3D 建立典型矿区采煤影响范围含水层结构变异模型，揭示煤层开采引起的含水层结构变异规律。研究结果表明，采空区上方导水裂隙带发育规律是两边略高中间略低的马鞍形，两边发育高度为 105.7 m，中间发育高度为 97.5 m。模拟值与实测拟合效果较好，可以有效预测采煤后含水层空间结构变化。

(2)根据地质钻孔的地层岩性数据统计分析，利用 TPROGS 建立含水介质模拟的马尔科夫转移概率地统计模型，揭示研究区含水层空间结构非均质演化规律和趋势。研究结果表明，开采煤层厚度与渗透系数变异带发育高度基本呈近似线性关系，采厚越大，渗透系数变化幅度越大。该模型能够较准确预测岩石的渗透系数 K，其计算精度要远远高于以往的经验公式。

(3)根据地下水系统中含隔水层、煤层赋存关系，结合导水裂隙、地表拉伸裂隙、开采沉陷等含水层结构变异受控因素，建立变参数变结构的地下水数值模拟模型。利用模型分析预测研究区不同开采情景下的地下水流场演变，揭示了群矿采煤驱动下盆地尺度地下水循环模式和水资源演化规律。研究结果表明，煤层开采形成采动裂隙发育基本限制在完整基岩内，使得隔水底板粘土岩发生弯曲变形，承压含水层水位下降形成人为“上层滞水”，对第四系潜水含水层结构破坏影响甚微；隔水层有效厚度变薄局部地区，由于采动裂隙切穿隔水岩层，导致该区潜水含水层消失；同时采煤造成的人为“溯源侵蚀”，引发原本隔离的地下水系统间的地下水袭夺现象，矿井水补给量适当增加。

(4)开展采煤过程中和煤层开采后地下水资源演化趋势与再分布的研究。结果表明，采空区影响范围内出现不同规模的地面裂隙或裂缝，降水入渗补给由活塞式转变为捷径式。同时采空塌陷使得原有砂岩、页岩含隔水系统被破坏，裂隙水被大量疏干排出，地下水位下降，由于矿坑排水使补给量增加；采空塌陷及采空区增加了地下水储水空间，改变了补径排特征，天然基流量减少转化为矿坑水，改变了地下水系统对径流的调蓄作用，地表径流不仅受降水、地下水调蓄作用控制，还受到矿坑疏排水影响，使得水资源时空分布不均加剧。

(5)群矿开采驱动下含水层结构变异是长治盆地地下水补径排循环模式改变的主导因素，煤层开采对地下水系统的破坏是永久不可逆的，破坏程度还在不断加剧。即使煤矿关闭后，不开采不排水并不代表停止破坏地下水资源，被破坏的地下水系统基本无法恢复，尽管不排水，仍有较大水量涌入矿井采空区成为被污染的老窑水。

3　主要创新点

(1)利用 FLAC3D 建立的含水层结构变异模型，并与实测数据有较好的拟合效果，可以有效预测采煤后含水层空间结构变化。

(2)构建的 Markov 转移概率地统计模型能够较准确预测岩石的渗透系数 K，其计算精度要高于以往的经验公式，Markov 转移概率地统计模型可以用于研究区含水层渗透系数计算，能够为水循环机制研究提供基础数据。

(3)建立变参数变结构的地下水数值模拟模型，改进了传统的确定性地下水模型，提高模拟的可靠性和准确性。利用模型分析预测研究区不同开采情景下的地下水流场演变，揭示了群矿采煤驱动下盆地尺度地下水循环模式和水资源演化规律，为地下水资源合理开发、科学管理及环境保护提供技术依据。

关键词： 含水层结构变异；群矿开采；地下水；数值模拟；长治盆地
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Numerical Simulation of Structural Variation of Aquifer Effect on Regional Groundwater Circulation

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The destruction of groundwater resources caused by coal mining is the main bottleneck restricting the sustainable development of economy and environment in coal mining area. The contradiction between mining of coal resources and protection of water resources will become more serious. China's coal-rich regions are mainly distributed in north and northwest China. Only coal reserves in Shanxi, Inner Mongolia, Shaanxi and Xinjiang provinces account for 73.1% of the total coal reserves. Groundwater resources in these coal-rich areas are relatively poor. Severe water shortage accounted for 71% of key mining areas and 40% of serious water shortages. The serious damage to underground water resources exacerbated the shortage of water resources in the mining areas, which is particularly prominent in the energy province of Shanxi. The fundamental reason is that the mining caused structural changes in aquifers, resulting in damage to groundwater resources, so that the groundwater resources from the original quality of water available for exploitation into the pit of mine water and drain away, undermine the groundwater fill row, and destroyed the hydrological surface conditions, undermined the surface water cycle, thus affecting the regional groundwater cycle situation.

During the coal mining process, the destruction of the surrounding rock caused the change of the aquifer and the aquifer structure, coupled with the large amount of drainage of the mine water, the underground water flow field evolved to the groundwater circulation mode under the coal mining condition. After the mine has been closed, the groundwater flow field and the environment of the mine which has been disturbed by mining are changed again. The original aquifer and the mining disturbance fissure space is flooded again, the water chemistry environment also changes obviously at the same time, forms the new pattern of the groundwater environment circulation evolution after the coal mining. The evolution of groundwater cycle pattern during coal mining and coal mining has four-dimensional dynamic evolution, nonlinearity and complexity. In the past, most researches have been carried out from the perspective of hydraulic conductivity and mining water-inrush mechanism of single coalmine mining, and the influence mechanism of dynamic evolution of mining fissures on the structural variation of aquifers. However, this is the key to reveal the redistribution rules of groundwater resources caused by coal mining and to clarify the true pattern of regional groundwater cycle evolution under coal mining conditions. Under the coal mining condition, the groundwater resources are destroyed and the groundwater environment is deteriorated. It is revealed that the real law of regional water cycle evolution after coal mining is the key issues to realize the regulation and optimization of water resources, and to realize the economic and resources and environmental development.

Based on the theoretical analysis and numerical simulation, this paper studies the influence of aquifer structure variation on the regional groundwater cycle mechanism in the mining area of Lu'an, Changzhi basin, Shanxi, and reveals the variation of regional aquifer spatial structure after coal mining, to identify the true state of redistribution of groundwater resources during coal mining, to further develop a new theory of groundwater system evolution under the variation of aquifer spatial structure, and to enrich regional water cycle research under changing environment; The characteristics of underground water circulation evolution and redistribution of groundwater resources, to a certain extent to achieve the aquifer spatial structure variation on the groundwater cycle evolution mechanism of the characteristics of innovation and theoretical breakthroughs, this study is not only of practical significance for coal mining area economy, resources and the environment can be the sustainable development, and it has theoretical value for the study of groundwater cycle evolution under the condition of group mining. It provides reference for the sustainable utilization of groundwater resources and the planning and design of water conservation for coal mining.

1 Main research contents

(1) The influence of spatial and temporal evolution of mining fissures on the structural variation of regional aquifers. Through the research on the characteristics of time-space distribution and dynamic evolution of overburden deformation, failure and

mining fissure in typical mining area, the change of buried depth, thickness and boundary condition of water-bearing medium, the porosity and fracture rate The characteristics of heterogeneity of water medium in the influence range of coal mining are expounded. Through the study of the mechanism of mutual conversion between water-bearing medium and water-conducting property, the results of coal seam mining-induced and the variation model of aquifer structure in mining area affected by coal mining is established.

(2) Effect of aquifer structure variation on regional water cycle driven by group mining. Based on the in-depth study on the heterogeneous evolution characteristics and evolution trend of the regional aquifer caused by coal mining in the group, the latest information, data and data of the groundwater in the area after coal mining are obtained, and the regional groundwater flow pattern the evolution of hydrogeological structure and the coupling of groundwater flow patterns under the influence of coal mining in coal mines, and the influence mechanism of heterogeneous evolution of aquifer spatial structure on regional water cycle, and the establishment of regional groundwater circulation evolution model.

(3) The evolution trend and redistribution of groundwater resources driven by coal mining. Based on the research results of groundwater cycle evolution under the driving of coal mining, the evolution trend and redistribution of groundwater resources during coal mining and coal mining are carried out. The evaluation model of water resources under mining conditions is established, and comprehensive evaluation of basin water resources, revealing the status, characteristics, changing regularity and availability of redistributed groundwater resources after coal seam mining.

2 The main research results

(1) A structural variation model of aquifer influenced by coal mining in typical mining area was established on FLAC3D, based on the study of mechanism of water-retaining and water-conducting mutual transformation of water-bearing medium, revealing the variation law of aquifer structure caused by coal mining. The results show that the development law of the hydraulic fractured zone above the mined-out area is slightly saddle-shaped with the height of 105.7 m on both sides and the middle height of 97.5 m on both sides. The simulation results are in good agreement with the measured data, which can effectively predict the spatial structure of the aquifer after coal mining.

(2) Based on the statistical analysis of stratigraphic lithology data of geological boreholes, TPROGS is used to establish the Markov transition probabilistic geostatistical model for the simulation of water-bearing media, revealing the heterogeneous evolution and trend of the aquifer spatial structure in the study area. The results show that there is a linear relationship between the thickness of the coal seams and the height of the variation zone of the permeability coefficient. The bigger the thickness is, the bigger the variation of the permeability coefficient is. The model can accurately predict the permeability coefficient of rock K, the calculation accuracy is much higher than the previous empirical formula.

(3) According to the controlling factors of water-bearing strata and coal seams, the numerical simulation model of variable-parameter groundwater system is established based on the control factors of aquifer structure variation such as water-conducting fissure, surface tension fracture and mining subsidence. The evolution of groundwater flow field under different mining conditions in the study area is predicted by model analysis, and the groundwater cycle pattern and water resources evolution rule driven by coal mining are revealed. The results show that the development of mining fissures in coal seams is basically confined in intact bedrock, which makes the clay strata bent and deformed, and the water level of confined aquifers decreases to form the "upper stagnant water", and the aquifer structure of Quaternary and the effective thickness of the aquitard are thinned. In some areas, the aquifer is cut off because of mining fissures cut through the aquifers, and the man-made "trace-source erosion" caused by coal mining has caused the original isolated groundwater system between the phenomenon of groundwater seized, an appropriate increase in mine water recharge.

(4) The trend and redistribution of groundwater resources during coal mining and coal mining. The results show that ground fissures or cracks of different scale appear in the affected area of the mined - out area, and the precipitation infiltration recharge is changed from piston type to shortcut type. At the same time, the original sandstone and shale containment system is destroyed, the groundwater level is decreased and the water supply is increased. The ground subsidence and groundwater increase the groundwater storage Space, changing the characteristics of the fill row, natural base flow reduction into pit water, changing the groundwater system on the role of runoff storage, surface runoff is not only affected by precipitation, groundwater storage control role, but also by the mine drainage effect, making the spatial and temporal distribution of water resources increased.

(5) Variation of aquifer structure driven by group mining is the main factor of Changzhi basin groundwater recharge row circulation pattern change. The damage of coal mining to groundwater system is irreversible and the damage degree is increasing. Even if the mine is closed, not mining does not mean not stop the destruction of groundwater resources, damaged

groundwater system can not be restored, although not drainage, there is still a large amount of water into the mine go to become contaminated old pit water.

3 The main innovation

(1) The aquifer structure variation model established by FLAC3D has good fitting effect with the measured data, which can effectively predict the spatial structure change of the aquifer after coal mining.

(2) The Markov transition probabilistic geostatistical model can predict the permeability coefficient K of the rock more accurately than the previous empirical formula. The Markov transition probability geostatistical model can be used to calculate the permeability coefficient of the aquifer in the study area. And provide the basic data for the research of water cycle mechanism.

(3) The numerical simulation model of groundwater system with variable parameter structure is established, and the traditional deterministic groundwater model is improved to improve the reliability and accuracy of simulation. Based on the model analysis, the evolution of groundwater flow field under different mining conditions was predicted, and the groundwater cycle pattern and water resources evolution rule driven by coal mining were revealed. The technical basis for rational exploitation, scientific management and environmental protection of groundwater resources was provided.

Key words: aquifer structural variation; group mining; groundwater; numerical simulation; Changzhi Basin

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