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THE EVOLUTION PROCESS AND MECHANISM OF LAND SUBSIDENCE IN TYPICAL AREA, BEIJING

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图书在版编目（CIP）数据

北京市典型地区地面沉降演化过程与机理分析/陈蓓蓓等著. —北京：中国环境出版社，2015.2
（环境与资源博士文库. 第 3 辑）
ISBN 978-7-5111-2206-3

Ⅰ. ①北… Ⅱ. ①陈… Ⅲ. ①地面沉降—研究—北京市 Ⅳ. ①P642.26

中国版本图书馆 CIP 数据核字（2015）第 010598 号

出 版 人　王新程
责任编辑　沈　建
助理编辑　郑中海
责任校对　尹　芳
封面设计　彭 [illegible]

出版发行　中国环境出版社
（100062　北京市东城区广渠门内大街 16 号）
网　　址：http://www.cesp.com.cn
电子邮箱：bjgl@cesp.com.cn
联系电话：010-67112765（编辑管理部）
010-67113412（教材图书出版中心）
发行热线：010-67125803，010-67113405（传真）
印　　刷　北京中科印刷有限公司
经　　销　各地新华书店
版　　次　2015 年 4 月第 1 版
印　　次　2015 年 4 月第 1 次印刷
开　　本　880×1230　1/32
印　　张　9.125
字　　数　170 千字
定　　价　32.00 元

项目资助

1．国家基金（重点项目）：北京地区地面沉降三维形变及演化机理研究（41130744/D0107）；

2．国家自然基金（面上项目）：地下水降落漏斗区动静载荷演化诱发地面沉降机理研究（41171335/D010702）；

3．国家 973 计划课题：城市典型区域不均匀沉降信息获取与机理研究（2012CB723403）；

4．北京市自然科学基金（重点）：地面沉降对京津高速铁路运行影响及调控方法研究（8101002）。

缩写词索引

PS：永久散射体

InSAR：合成孔径干涉雷达测量技术

CBD：城市密集建筑群

NDBI：归一化建筑用地指数

MNDWI：归一化差异水体指数

SAVI：土壤调整植被指数

IBI：遥感建筑用地指数

DEM：数字高程模型

SBAS：小基线干涉测量技术

SVD：奇异值分解

SB：相干点

D-InSAR：差分干涉测量技术

SDFP：等值梯度法

摘 要

地面沉降是由自然和人为因素引起的地面标高损失的环境地质现象，严重时可能诱发一系列的灾害链，是一种永久性的不可补偿资源和环境损失。北京从 20 世纪六七十年代发现地面沉降以来，平原地区的地面沉降呈快速发展的态势。已经形成了南北两大沉降中心，地面沉降快速的区域，地表仍以每年30～60 mm的速度持续发展，区域地面沉降对北京许多城市基础设施均产生不同程度的危害和影响，严重影响着首都社会、经济、人民生活的可持续发展。本书在对国内外地面沉降监测方法、成因机理的研究现状，进行系统学习与总结的基础上，以北京市典型地区为研究区，采取小基线、PS 干涉测量方法融合技术，获取区域地面沉降监测信息。在区域浅表层空间不同的变异模式下，分析时间序列的不均匀沉降及其演化过程。进而研究地下水动态变化、载荷时空演化、地质构造与区域地面沉降的响应关系，定性与定量相结合阐明多元作用下的地面沉降的成因机理。本书的主要内容和结论包括以下几点：

1. 融合 PS 和小基线干涉测量方法时序地面沉降监测

采用融合 PS 和小基线干涉测量方法，获取了时序地面沉降

监测信息（2003—2009）。分析结果发现，该时段北京地区的地面沉降发展较为迅速，最大年沉降速率为 41.43 mm/a；从 InSAR 年沉降速率的趋势发现，地面沉降尤其是不均匀沉降的时空展布程度和范围仍会逐年加剧。

2. 典型区域地面沉降时序演变过程分析

在融合 PS（永久散射体测量）和小基线干涉方法测量地面沉降的基础上，以区域浅表层空间[地铁、城市密集建筑群（CBD）、立体交通网络设施]为参考，以 6 km^2 大小的正方形范围为移动窗口，选取 5 个典型的小区域，进行时间序列的不均匀沉降的演化分析：

1）典型区域 1：不同年度，区域地面沉降的季节性变化差异性较大。2004 年，季节性形变特征比较明显；2008 年，季节性形变特征波动性较大，最大沉降量出现在冬季；其空间演化特征基本是呈团状聚簇式分布。

2）典型区域 2：同年度内，时间上沉降波动明显，空间分布较为均匀；年度演化特征：春季较小形变量主要分布在北方向，其他季节，不同等级沉降量的 PS 点呈较为均匀的离散状分布。

3）典型区域 3：不同年度，区域地面沉降的季节性变化差异性较大；同年度内，PS 点的空间分布差异性均较大。

4）典型区域 4：区域地面沉降的季节性时空变异性较大。2004 年，PS 点季节的形变空间分布格局大体相同，差异性不大，且分布较为均匀；2008 年，季节变化的幅度不大，但是 PS 点的不均匀性较大，季节时空格局差异性也较大。

5）典型区域 5：地面沉降的季节性时空变异特征明显。2004 年，PS 点的沉降值差异较大，但空间分布较为均匀；2008 年，

区域的季节波动性较大，空间分布格局受前门—良乡—顺义断裂影响。

6）综合分析结果可以说明，浅地表空间利用的情况在一定程度上影响着区域的不均匀沉降态势：空间利用情况越简单，沉降的梯度相对越小，不均匀沉降趋势越小。

3．地下水漏斗动态变化与区域地面沉降响应分析

采用 GIS 空间分析技术，遥感技术、优化选取统计分析方法等，基于长时间序列的气象监测资料和地下水监测信息，系统分析了北京地区降雨时空演化特征，进而揭示了地下水漏斗形成及对降雨补给变化的动态响应关系。在此基础上，结合地下水动态长期观测网数据、InSAR（合成孔径干涉雷达测量技术）监测结果，系统分析了北京地区地下水漏斗动态变化和地面沉降响应演化过程。

1）系统分析了北京地区降雨时空演化特征，进而研究由于降雨量减少与城市化扩张，导致地下水有效补给减少，间接导致了地下水的长期过量开采，从而促使地下水流场的演化与地下水漏斗形成。

2）揭示了北京地区地下水降落漏斗的历史形成及时空演化特征。地下水漏斗形成于 1975 年，截止到 2001 年，地下水漏斗面积达到 1 000 km^2；扩展速率不断加快（12.5～34 km^2/a）；2005—2009 年，地下水漏斗中心主要在朝阳东部地区，地下水严重下降区域面积不断扩大，地下水降落漏斗的空间分布模式逐步向东北方向扩展。

3）基于 GIS 的空间分析与常规监测资料，分别揭示出北京五个典型地面沉降漏斗的形成和时空演化特征：朝阳区东八里庄

至大郊亭地面沉降漏斗、来广营地面沉降漏斗是沉降历史最长、最具代表性的两个漏斗；而以北京郊区（昌平沙河至八仙庄、大兴榆垡至礼贤地、顺义平各庄）为代表的新的沉降区，虽然形成较晚，但沉降发展十分迅速，其中昌平沙河至八仙庄出现了北京最大累积沉降量 1 086 mm。

4）将时间序列 InSAR 地面沉降形变响应信息，和年际地下水动态流场演化对比研究，揭示了地面沉降发生较为严重的地区也正是水位埋深较深的地区，主要分布在顺义天竺地区、朝阳地区及通州西北处，这说明北京地区地下水流场变化与地面沉降响应发展具有较好的一致性。分析进一步发现地下水漏斗与地面沉降漏斗空间展布特性并非完全吻合，说明了虽然北京地区地面沉降发生的主要原因是由于地下水的开采，但地面沉降的发展区域也与水文地质条件、可压缩层厚度、地层构造、开采地下水的层位等存在相关性。

5） 以不同变异条件下的 5 个典型区域为研究区，分析不同含水层系统地下水水位动态变化与地面沉降量点位关系：不同含水层系统演化对地面沉降的贡献不同；总体而言，地面沉降演化与潜水水位变化相关性较小，而与承压水水位动态变化相关性较大，且两者呈正比例的关系。

4. 区域载荷时空演化与地面沉降响应分析

借鉴基于遥感建筑用地指数方法，反演基于三指数的遥感建筑用地指数（以下简称 IBI），获取北京地区区域建成区（载荷）时空演化信息（2003—2009 年）；基于 InSAR 监测结果和 IBI 法，结合 GIS 空间分析方法，从不同尺度的像元角度出发，分析区域载荷变化与地面沉降的相关性。

1）在 NDBI、MNDWI、SAVI 反演的基础上，进一步采用 Erdas Modeler 工具反演基于指数的建筑用地指数（IBI），获取研究区建筑用地（载荷）时空变化信息，并进行精度验证。

2）基于 InSAR 监测结果和 IBI 法，结合 GIS 空间分析方法，从不同尺度的像元角度出发，分析区域载荷变化与地面沉降的相关性：

- 以每个 PS 点为单个研究对象，IBI 值取该点对应的栅格值，沉降速率即取 PS 点值，采用 Spearman 秩相关系数法来研究载荷密度与地面沉降的关系。研究发现沉降的不均匀性与载荷密度的大小存在正相关关系。
- 基于 20×20 窗口大小，采用回归分析方法，结合 GIS 空间分析，表明建筑用地和 PS 点沉降速率呈正相关关系。建筑用地即城市载荷的增加，会导致地面沉降的加剧，即载荷的增加对地面沉降的发展产生影响。
- 基于 GIS 空间平台，选取 100×100 的窗口大小，研究单体范围是 9 km^2，根据其空间分布和 PS 点的位置情况，共选取了 30 个采样单元，结果表明，北京地区密集的道路及巨大的车流量对道路的往复击打，即动静载荷的共同作用，在一定程度上对地面沉降产生影响。
- 选取的 5 个典型小区域为研究对象，分析结果表明不同浅地表变异条件下的 5 个研究区域，地面沉降的变化态势与 IBI 值的高低基本一致。即建筑密度越大（即 IBI 越大），地面沉降效应越显著。

3）总体看来，载荷的密度与沉降的不均匀性存在正相关关系，尤其在高沉降速率地区显示的较为明显；这说明高密度建筑群使得局部地面荷载增加，各单体建筑的附加沉降互相叠加，对

区域性地面沉降的贡献不容忽视。

5. 区域地质构造与地面沉降相关性分析

在重点分析地面沉降对地下水超量开采、动静载荷时空演化响应的基础上，分析常规地质资料数据，基于GIS空间分析平台，结合统计分析方法，定量与定性相结合揭示区域地质构造与地面沉降的相关性。

1）InSAR监测结果揭示出，研究区内的昌平八仙庄、朝阳来广营、东八里庄至大郊亭沉降区均位于顺义隐伏凹陷内。

2）构造运动对地面沉降的影响主要是研究区所处的构造单元在区域应力场的作用下整体呈缓慢下降趋势；断层上、下盘的相对升降运动对处于断层两盘的地面沉降速率差异有一定的影响。

ABSTRACT

Land subsidence is an environment geological disaster which is caused by natural and human factors, loss of ground elevation, which may induced a series of disasters chain, so it is a permanent and non-compensation resources and environmental losses. Land subsidence was discovered since the 1960 s in Beijing, it has the rapid development of the trend in the plain, now, the two largest centers of subsidence in south and north has been formed. In the most rapid developing area, land subsidence is still developing with the speed of 30-60 mm/a. Regional land subsidence has induced harm and impact with varying degrees on many infrastructures in Beijing, which has seriously affected the sustainable development of the social, economic, and people's lives.

In the book, I have learned and summarized the monitoring method and evolution mechanism on land subsidence at home and abroad systematically. Chose the typical settlement area as the study area, I have used the multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches, obtain

monitoring information of regional land subsidence. Under different situation of space development and utilization, I have analyzed the time series evolution of uneven settlement .Then researching that groundwater dynamic changes、 static and dynamic load evolution, geological structure are in the role of land subsidence, reveal the formation mechanism of land subsidence under the multi-role combining qualitative and quantitative methods. The main contents and conclusions are as follows:

1. Multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches to obtain settlement information

I have used the merge method of PS-InSAR and SBAS to get the monitoring information of land subsidence from 2003 to 2009.The analysis results shows: the developing speed of land subsidence is very quickly in this time of Beijing. The maximum settlement ratio is 41.43 mm per year; from the development trend of settlement ratio by InSAR method, it found that land subsidence especially the uneven settlement, whose temporal and spatial degree and range will be further increased year by year.

2. Analyze the time series evolution of uneven settlement in typical area

On the basis of obtain settlement information by multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches, reference to the different situation of space development and utilization, the square of 6 km^2 size is as the moving window, I have chosen five small typical area, analyzing the time series evolution of uneven settlement:

1) Typical area 1: In the different years, the differences of seasonal changes are larger.

Seasonal deformation characteristics are significant in 2004; the volatility of seasonal deformation characteristics is obviously, the maximum settlement ratio is in winter; the feature of spatial evolution is clustered distribution of pellets.

2) Typical area 2: Within one year, settlement fluctuates significantly temporally, the spatial distribution is more uniform; Evolution of annual: in spring, the smaller deformation is mainly distributed in the north, other seasons; the PS points of different scale are distributed as discrete-like uniformly.

3) Typical area 3: Different years, the differences of seasonal changes are exist; in the same year, for PS point, the differences of spatial distribution is obviously.

4) Typical area 4: For regional settlement, temporal and spatial variability in different seasons is obviously.2004, spatial settlement distribution pattern of PS points are about same, the difference is little in different seasons, while, the distribution is more evenly; 2008, the amplitude of seasonal variation is moderate, but the settlement of PS points is unevenly, temporal and spatial variability in different seasons is more significant.

5) Typical area 5: Land subsidence which temporal and spatial variability of different seasons is significant, in 2004: the settlement

value of PS points are differential, but the spatial distribution is even; in 2008, seasonal volatility is very obviously, spatial distribution pattern is controlled by qianmen-liangxiang-shuiyi fault.

6) The comprehensive analysis results suggests: the complex situations of space development and utilization which affects the trend of the region's uneven settlement; the easier situation of space development and utilization, the smaller of settlement gradient, the less obviously of uneven settlement trend.

3. Dynamic change of groundwater funnel and regional land subsidence response

Apply GIS spatial analysis, remote sensing techniques, statistical analysis and so on, on the basis of meteorological monitoring data with long time series and groundwater monitoring information, the study gives a systematical analysis of temporal and spatial evolution of rain in Beijing, then reveal that the formation of groundwater funnel and the response for the precipitation recharge. At last, it combined the groundwater dynamic long-term observation network data, InSAR monitoring results, research the procedure of dynamic change of groundwater funnel and regional land subsidence response.

1) Analysis temporal and spatial evolution of rain in Beijing systematically; As the decreasing precipitation and rapid expansion of urbanization, which reducing the amount of effective recharge of precipitation to groundwater, led to long-term over-exploitation of groundwater indirectly, while induced regional land subsidence.

2) Reveal that the formation and evolution of ground water funnel in Beijing: the ground water funnel has formed in 1975, up to 2001, the area of ground water funnel is 1000 km^2, whose expansion rate is accelerating (12.5-34 km^2/a); 2005-2009, the groundwater funnel center is located in the eastern of chaoyang region, the area whose groundwater are declining seriously are expanding, the spatial expansion pattern of ground water funnel is extending to the northeast gradually.

3) Based on GIS spatial analysis technology and the conventional monitoring data, it revealed the formation and evolution of five typical settlement cone in Beijing: dongbalizhuang-dajiaoting settlement funnel、laiguangying settlement funnel in chaoyang district, which are the longest history of land subsidence and the most representative; in the Suburbs, changing chahe-baxianzhuang funnel、daxing yufa-lixian、shunyi pinggezhuang, these are new representative settlement area, through they are formed lately, but the expansion is very fast, the maximum cumulative settlement is 1,086 mm which appeared in changing chahe-baxianzhuang funnel 1,086 mm.

4) combining the settlement response information by InSAR technology with the dynamic evolution of ground water level, which revealed that It was revealed that a consistency existed between the groundwater funnel and spatial distribution characteristics of land subsidence cone but not entirely.This suggests: in Beijing area, although land subsidence occurred mainly caused by the exploitation of groundwater, the expansion area of land subsidence are correlation to the hydrogeological conditions, thickness of the compressible

layer, stratum structure, groundwater extraction layer.

5) Choosing five typical areas whose have different space development and utilization, it analyzed the relationship between dynamic change of ground water level in different aquifer system and settlement for PS points: different aquifer systems make different contribution to land subsidence; overall, the evolution of land subsidence has the low correlation to the unconfined aquifer water, but which has the high correlation to the confined aquifer, and both was in direct proportion.

4. Static and dynamic load evolution and response of land subsidence

Draw method based on building land index by remote sensing technology, the study inversed the remote sensing construction Index based on three index (IBI index), obtaining the temporal and spatial evolution information of built-up areas in Beijing(2003-2009); based on the InSAR monitoring results and IBI index method, combining the GIS spatial analysis methods, in the view of different pixel scales, it analyzed the relationship between temporal and spatial evolution of load and land subsidence.

1) Based on the inversion of indexs (NDBI、MNDWI、SAVI), using the Erdas Modeler method to inverse the IBI index, the study obtained the temporal and spatial evolution information of built-up areas (Static and dynamic load) .Then the accuracy was verified.

2) Using the InSAR monitoring results and IBI index method, GIS spatial analysis methods, in the view of different pixel scales,