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——以山西省太原市为例

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前 言

自 1891 年中美洲墨西哥城发现地面沉降以来，目前世界上已有 50 多个国家和地区发生了不同程度的地面沉降。我国于 1921 年在上海最早发现地面沉降，到目前已有 96 个城市和地区出现了严重的地面沉降问题。地面沉降已成为一个全球性的、威胁人类生存环境的重大环境地质问题。鉴于地面沉降危害的严重性、分布的广泛性和成因的复杂性，近半个多世纪以来，世界上已有众多研究者对地面沉降开展了内容广泛而深入的研究。联合国教科文组织(UNESCO)与国际水文科学协会(IAHS)等已组织召开了 7 届国际地面沉降会议，我国也召开了 6 届全国性地面沉降学术讨论会。

根据地面沉降区的环境地质背景和沉降产生的地质成因，可划分出如下 3 种地面沉降地质模式：冲积平原模式、三角洲模式和断陷盆地模式。目前，对于前两种模式，尤其是沿海三角洲模式研究较多。在国外，以意大利的波河三角洲、英国的伦敦等地为代表；在国内，最为突出的是以上海为代表的长江三角洲、以天津为代表的环渤海地区等。相对于前两种沉降模式而言，断陷盆地的地面沉降有其特殊性，具体表现在：①内陆盆地特定的沉积环境，造就了土的物源、展布方式、物质组成、结构特征及物理力学性质等方面的独特性；②人类活动与构造作用综合影响，导致了地面沉降成因及发生机理的复杂性。

太原市是山西省政治、经济和文化中心，是我国的能源重化工基地。该市于 20 世纪 50 年代出现地面沉降，到 2000 年沉降涉及范围已达 585km^2，最大沉降量 2 815mm。地面沉降已给太原市的开发建设和人民群众的安居乐业带来了一系列的影响，严重制约着区域社会经济的发展。开展太原市地面沉降研究，对于减轻当地沉降危害、改善居民生存环境有着重要的实际意义。太原市属典型的断陷盆地，基底构造复杂，且断裂活动仍在继续，新生代沉积物岩相与厚度变化大，盆地内地下水超采严重，其沉降原因、机理及治理思路均有别于沿海地区。因此，在太原市开展地面沉降研究将有助于丰富地面沉降研究的理论与方法体系，有着重要的科学意义。

本书以监测—成因分析—机理分析—模拟—预测与控制为研究主线，通过对太原市地面沉降监测数据的分析，揭示了地面沉降的时空变化规律和引发地面沉降的主导因素，分析了地面沉降机理及地质环境对沉降分布的影响，建立了地面沉降数值模型，模拟了不同地层深度地面沉降的分布情况，进而提出有效控制地面沉降的措施和方案。限于经费和水平，这些工作仍然是初步的，有待进一步深入和完善。

感谢山西省地质工程勘察院周兴平高级工程师、王贵喜教授级高级工程师在资料收集和野外工作中给予的大力支持和帮助。感谢中国地质大学工程学院的项伟教授在室内土工实验和书稿撰写过程中提供的帮助和指导。

本书参考引用了大量的文献和图件，已在文中注明，对笔者有启发意义的但未在文中引用的文献都已在参考文献中列出。在此，向这些文献的作者表示感谢。

在本书出版过程中，硕士生闫春淼同学完成了部分图件的绘制工作，博士生崔德山同学做了部分校排工作，赵颖弘编审对本书提出了宝贵意见，在此一并表示感谢。

限于笔者的水平，书中不足之处在所难免，敬请读者批评指正。

笔　者

2006 年 4 月 30 日

摘 要

地面沉降是一种由自然和人为因素引起的地面标高缓慢降低的环境地质现象。自1891年中美洲墨西哥城发现地面沉降以来，目前世界上已有50多个国家和地区发生了不同程度的地面沉降。1921年我国在上海最早发现地面沉降，到目前已有96个城市和地区出现了严重的地面沉降问题。地面沉降已成为一个全球性的、威胁人类生存环境的重大环境地质问题。根据地质成因可将地面沉降划分为3种沉降地质模式，即冲积平原模式、三角洲模式和断陷盆地模式。

鉴于地面沉降危害的严重性、分布的广泛性和成因的复杂性，在近半个多世纪里，世界上有众多的研究者对地面沉降开展了内容广泛而深入的研究，并在地面沉降的原因与机理、数值模拟与预测、监测与防治、灾害评估等方面取得了卓有成效的研究成果。联合国教科文组织(UNESCO)与国际水文科学协会(IAHS)已组织召开了7届国际地面沉降会议，我国也在上海和天津召开了6届全国性地面沉降学术讨论会。但这些研究主要集中在前两种类型上，而关于内陆断陷盆地的研究则相对较少。

太原市是山西省政治、经济和文化中心，是我国的能源重化工基地。该地自20世纪50年代出现地面沉降以来，到2000年其涉及范围已达453.3km^2，最大沉降量2 815mm。地面沉降已给城市的开发建设和人民群众的安居乐业带来了一系列的危害，严重制约着本地经济的可持续发展。开展太原市地面沉降研究对于减轻当地沉降危害、改善居民生存环境有着重要的实际意义。此外，从地质构造上讲，太原属典型的断陷盆地，基底构造复杂，新生代沉积物岩相与厚度变化很大，且断裂活动仍在继续，地下水超采严重，其沉降原因、沉降机理及治理思路均有别于沿海地区。因此，在太原开展地面沉降研究将极大丰富地面沉降研究的体系，有着重要的理论意义。

本书在借鉴前人研究的基础上，选取太原盆地作为研究区，以监测—成因—机理—模拟—预测与控制为研究主线，通过对地面沉降监测数据的分析，揭示地面沉降的时空变化规律和引发地面沉降的主导因素，探究地面沉降机理，分析地质环境对沉降分布的影响，建立地面沉降数值模型，预测地面沉降趋势，进而提出有效控制地面沉降的措施和方案。具体研究内容如下：

(1)地面沉降的时空分布规律

据太原市93个Ⅱ等水准测量点实测资料，分析了地面沉降的历史演变特征，将其划分为3个沉降阶段；根据地面形成规模划分出2处沉降区(西张沉降区和城区沉降区)，4个沉降漏斗中心(西张沉降中心、万柏林沉降中心、下元沉降中心、吴家堡沉降中心)。1956—1981年为地面沉降中心初步形成阶段：1965年以前无明显地面沉降现象；1965—1970年是缓慢沉降时期；1970—1981年是地面沉降不均匀发展时期，在此期间，吴家堡沉降中心已形成。1981—1989年为地面沉降快速发展阶段：地面沉降涉及范围南北长约37km，东西宽约12km，沉降面积441.8km^2；1981—1989年期间，形成2处沉降区(西张沉降区和城区沉降区)，4个沉降漏斗中心(西张沉降中心、万柏林沉降中心、下元沉降中心、吴家堡沉降中心)。1989—2000为地面

沉降持续急剧扩展阶段：沉降波及范围南北长约 38km，东西宽约 12.5km，沉降面积 453.3km^2；1989—2000 年期间，4 个沉降漏斗面积迅速扩展。

对分层标数据进行分析发现，不同深度地层压缩量的变化规律主要和中深层地下水位和孔隙水压力的变化呈现一致性。太原市深部的土层尚未固结，在应力变化下仍在沉降。并且地层不同深部压缩量不同，对地面沉降的贡献值也不同。

(2)地面沉降成因分析

依据 1981—2000 年晋祠地震基准台跨断层Ⅰ等短水准高程实测资料，发现晋祠下降盘位移量占绝大部分水准点沉降量的 1%～12%。由此可见，断裂活动虽然对太原市地面沉降有一定的贡献，但决非主要原因。从时间序列上来看，在 1997 年以前晋祠断裂活动下降盘位移量的时间变化规律与各个水准点在年沉降量变化趋势上无相似性。到 1997 年以后，晋祠断裂活动下降盘位移量的趋势与个别水准点的趋势出现一致性的规律。主要原因是 1997 年以前太原市年沉降量较大，构造活动引起的沉降量在总沉降量中所占的比例相对较小。到 1997 年以后有的地区年沉降量开始变小，构造活动在沉降过程中的贡献作用开始显现出来。这一发现说明虽然构造并非太原市地面沉降的主要原因，但是当沉降进入到微沉阶段，构造活动的作用将凸现出来，它对地面沉降的影响作用将不能忽视。

通过分析中深层地下水开采—地下水位变化—地面沉降发展的时间演变过程，发现：①1956—1981 年地下水开采总量不大，水位下降平缓，相应地，地面沉降发展曲线较为平稳；②1981—1989 年地下水开采进入急速增长时期，地下水位大幅度下降，相应地，此阶段为地面沉降发展的转折点，沉降速度急剧加大；③1989—2000 年，地下水开采强度有所缓和，地下水位下降速度有所减缓，但沉降仍在急速扩张，这主要是由于地下水位下降—地面沉降过程中的滞后效应引起的。以上分析表明太原市地下水开采—地下水位下降与地面沉降的时间演变过程是相符的。

通过对比不同年份中深层地下水水位降落漏斗和地面沉降漏斗的空间分布，发现水位漏斗主要发生在西张地区和城区，在西张地区形成西张水位降落漏斗中心，城区形成万柏林、下元、吴家堡和北营漏斗中心；而地面沉降的漏斗也主要发育在西张与城区两个地区，主要形成 4 个沉降中心，即西张、万柏林、下元、吴家堡沉降中心，沉降波及和分布范围与水位降落漏斗中心的位置比较相近。

由此可以看出，太原市地面沉降主要是由于过量抽取中深层地下水造成的。另外，当地下水位下降后，地面沉降存在滞后效应，沉降漏斗的发展滞后于水位漏斗的发展。

(3)地层特点和构造对地面沉降空间分布的影响

对比地下水位资料与地面沉降资料，发现地面沉降漏斗与地下水位降落漏斗的空间分布基本相近但不完全吻合，局部地区存在偏移，主要表现在：①水位降落漏斗与沉降漏斗的中心位置不重叠；②水位的降深与地面沉降的下降幅度并不成比例；③沉降主要发生在冲积平原区，洪积倾斜平原沉降不显著。对此，本书主要从断陷盆地特殊的地质条件出发，通过粘性土层累计厚度分布、粘性土层与粗颗粒土层的组合特征、不同分区各深度土的力学特征值与上述偏移的对比分析，认为太原市地层的空间异质性影响着地面沉降的分布。

相对于粗颗粒的砂砾质土，细颗粒的粘性土更容易发生沉降。因此，当外界条件相同时，粘性土的厚度差异就成为造成地面沉降量差异的重要因素。一般来讲，地层中粘性土的累计厚度越大，压缩总量也越大，砂砾石层的压缩量小于相同有效应力增量作用下粘性土的压缩

量。通过对比太原市地面沉降等值线图和太原市粘性土等厚度图，发现西张地区的地面沉降漏斗相对于水位漏斗明显向东偏移，东边恰是粘性土厚度较大的一侧；万柏林沉降漏斗相对于水位漏斗向南偏移，下元沉降漏斗较水位漏斗向西偏移，都是偏向粘性土厚的一侧。

另外，粘性土连通性差、渗透性低，在受压时孔隙水不易排出，水头压力转移所需时间较长，从而使其压密变形缓慢，较地下水位下降有较长的滞后和延迟。在地下水开采强度相同且粘性土累计厚度相同时，若粘性土的层数较多(即单层厚度较小)，则粘性土层释水快且充分，应力消散较快，沉降速率较大；反之，沉降速率相对较小。吴家堡水位漏斗并不是太原市地下水位降落最大处，但地面沉降量却是太原市最大，主要原因是吴家堡地层中粘性土累计厚度较大且多与砂质土互层(即粘性土间层厚度小)，当地下水位下降时，粘性土易于排水，压缩速度快且压缩量较大。亲贤—武宿一带的地下水位漏斗区并未形成地面沉降漏斗，主要是由于这一带粘性土层巨厚，且几乎连为一体，中间只夹有小块含水透镜体，当地下水位下降时不易排水，压缩非常缓慢。西张地区单层粘性土层虽然较薄但粘性土累计厚度小，因此地下水位降落幅度虽然较大，但沉降量却相对较小；万柏林—下元地区介于西张与吴家堡之间，粘性土的层数多于西张但少于吴家堡，其地面累计沉降量较西张大，但远小于吴家堡地区。

利用太原市 32 个钻孔资料统计出的太原市不同地区平均物理力学特征值表明，西张地区和太原市中心区的砂层较为密实，而北营、万柏林、下元区相对来说较松散，吴家堡地区的砂层最为松散。各分区的压缩性能基本都为中等压缩性，但是万柏林地区、下元地区压缩系数相对较小，西张、北营和太原市 3 个区压缩系数值较为接近，而吴家堡地区的压缩值偏大。再从液性指数来看，西张地区的粘性土液限值最小，其次为万柏林、下元和太原市 3 个区，液限值最大的为吴家堡区，一部分粘性土处于软塑状态。由此可知，吴家堡地区压缩系数较大、粘性土液限值偏大是其地面沉降量为全区最大的部分原因，而西张地区、太原市区、北营地区的这些指标值接近且相对较小，是其沉降量较小的部分原因。

综上所述，太原市地层的空间异质性对地面沉降分布有如下影响：①与地下水位降落漏斗相比，地面沉降漏斗偏向于粘性土层较厚的一侧；②地层组合(粘性土的夹层数、单层厚度等)对地面沉降的空间分布影响较大，沉降多发生在粘性土夹层多、单层厚度较小的地区；③土的力学性质的差异是影响沉降分布的重要因素。

此外，太原市地面沉降的展布方向和发展趋势明显的受到基底构造的制约。通过对比地面沉降和构造的空间分布特征发现：该区 4 个地面沉降中心均位于太原盆地中部 SN 隐伏断裂线附近；4 个沉降漏斗分别分布在 3 个次级构造沉降区，而且各沉降漏斗的轴线方向与附近构造线方向基本一致。构造运动对地面沉降有 3 方面的控制性作用：一是为地面沉降的产生提供了物质环境；二是直接引起差异沉降或由于盆地拉张引起地面垂向下沉；三是限制了地面沉降向周围的扩展。西张沉降漏斗向南的发展受到三给地垒的限制，沉降中心位于城北凹陷，主要发展趋势向北，发展方向和水位降落漏斗的发展方向一致；万柏林和下元沉降漏斗中心位于市区凹陷内，三给地垒限制了其向北的发展；吴家堡地区由于地层结构、粘性土厚度及土的工程力学性质的特殊性，沉降中心位于亲贤地垒上，但由于南北均为凹陷，漏斗均向南北方向发展，西温庄隆起限制了该漏斗的发展。

(4)太原市地面沉降机理分析

在太原市吴家堡沉降中心取原状土样，进行室内高压固结实验，研究发现：①地面沉降是由于抽取地下水使土的结构和物理力学性质发生变化而引起的，并且在抽水→稳定→回灌的

循环过程中，土的有效应力的变化和地面沉降的变化(即固结压密和回弹过程)滞后于地下水的变化；②地面沉降过程中，土中的孔隙水压力的减小和有效应力的增加是同步进行的，并且孔隙水压力的消散过程决定了地面沉降的速度；③在抽水→稳定→回灌的循环过程中，土层承受着加荷→卸荷的过程，土层的回弹系数随着压力的增加而减小。

(5)太原市地面沉降的模拟、预测和防治

粘土层在地下的非均匀分布导致了各压缩分层沉降量及其水平分布的差异，了解不同压缩层的沉降分布规律对地面沉降的控制有着重要的指导意义。本书采用三维有限差分地下水流模型 MODFLOW 中的子程序夹层包(IBS)，在对地层、边界条件的概化、模型的校正基础上，模拟出太原市不同地层的沉降分布规律。模拟结果发现，压缩量最大的层位为第一压缩层、第二压缩层和第七压缩层。西张地区沉降量最大层位为第三压缩层，万柏林、下元地区压缩量最大层位为第一、二压缩层，而吴家堡、小店地区的主要压缩产生在第四、五、六、七层。因为西张地区主要在第三压缩层产生沉降量，其他层位沉降较小，所以西张地区应该避免抽取与第三压缩层毗邻的第一承压含水层中的地下水，而万柏林、下元地区压缩量主要在第一、第二压缩层，应该尽量少抽取潜水—微承压含水层和第一承压含水层中的水，吴家堡、小店地区是太原市地面沉降量最大的地区，而它们的沉降量主要产生在深层，即第四、第五、第六、第七压缩层，所以该地区应该避免抽取深部的承压水(即第二承压含水层中的水)。

ABSTRACT

Land subsidence is an environmental geo-hazard that occurs due to gradual downward movement of the land. It is a differential subsidence of the earth surface with respect to the surrounding terrain. Land subsidence has emerged in more than 50 countries all over the world since 1891 when the first case of land subsidence was found in Mexico City. In China, the first case of land subsidence was found in Shanghai City in 1921. By far, there have been 96 cities where severe land subsidence was found, and the total affected area has been more than 49 000 km^2. In general, land subsidence has become a serious environmental geological problem which occurs all over the world and poses great threats on human society. According to its geological causes, land subsidence can be classed into three type geologically, i. e. the type of alluvial plain, the type of delta, and the type of faulted basin.

In the past 50 years, a lot of researches about land subsidence have been carried out, and our understanding of the causes and mechanism of land subsidence and capability of numerical modeling, prediction, monitoring, prevention, control, and risk assessment of land subsidence have been greatly improved. By far, UNESCO and IAHS have sponsored seven international symposiums on Land Subsidence. China has also organized six national symposiums on Land Subsidence. However, most of the studies have been focused on the former two types, while little on the type of faulted basin.

Taiyuan City, the political, economic, and cultural center of Shanxi Province, is one of the energy and industry bases in China. However, Taiyuan City has been suffering from land subsidence. The land subsidence occurred in 1950s, and expanded to the extent of 585 km^2 by 2000. The maximum accumulated subsidence has reached 2 815 mm in 2000. Land subsidence has caused a lot of losses, restricting sustainable development of Taiyuan. The research about land subsidence in Taiyuan City is practically significant because it can reduce the damage from the subsidence and improve the resident living conditions. In the term of geology, Taiyuan City is a typical faulted basin, with complex basal structure and great variable lithofacies and thickness of Cenozoic sediment. In addition, Taiyuan area is tectonically active, and the groundwater is severely over exploited. All these made it different from the coastal area of the causes, mechanisms, and controls of land subsidence in Taiyuan City. Thus, the research about the land subsidence is also theoretically significant, enriching greatly with the field of land subsidence researches.

In this works, the land subsidence in Taiyuan City was studied systemically. The main objectives of this works are: (i) to summarize the spatio-temporal patterns of land subsidence in Taiyuan City from the monitoring data, (ii) to determine the causes of the land subsidence, (iii) to find out the mechanism of the land subsidence, (iv) to analyze the effect of

geologic environment on temporal patterns of the land subsidence, (v) to predict the trend of the land subsidence through numerical simulation, and (vi) to put forward the control measures of the land subsidence.

(1) *Spatio-temporal patterns of land subsidence in Taiyuan City*

According to the data from 93 second-class leveling sites in Taiyuan City, three stages were divided spatially, and two land subsidence zones (i. e. the Xizhang zone and Urban zone) with four land subsidence centers (the Xizhang center, Wanbolin center, Xiayuan center, and Wujiabao center, respectively) were divided temporally.

●Incipient stage (1956—1981)

There was no obvious land subsidence before 1965, a slow subsidence in 1965—1970, a non-uniform subsidence in 1970—1981 when land subsidence center of Wujiabao came into being.

●Developing stage (1981—1989)

At the end of the period, the two land subsidence zones and the four land subsidence centers came into being, and the area affected by land subsidence was about 441.8km^2, with 37km in length (NW direction) and 12km in width (EW direction).

●Fast expanding space stage (1989—2000)

By 2000, the area affected by land subsidence was about 585 km^2, with 39km in length (NW direction) and 15km in width (EW direction).

(2) *Causes of land subsidence in Taiyuan City*

First-order leveling altitude data from Jinci seismic stations (BM1-BM3 leveling sites) located across the Jinci fault show that downward side of Jinci fault had subsided 21.88 mm from 1981 to 2000, accounting for 1%~12% of the total land subsidence volume. The data prove tectonic movement is one of the causes of land subsidence in Taiyuan City, but not the major one. Before 1997, subsiding volume of the downward side of Jinci fault showed no similar trend with land subsidence volume of any leveling sites. However, consistent trend was found between them after 1997. It is thought that subsidence volume caused by tectonic movement accounted for little proportion of the total volume for great land subsidence before 1997, and much proportion for decreasing land subsidence after 1997. It is concluded that tectonic movement is not the major cause of land subsidence in Taiyuan City, but should be considered when land subsidence becomes slight.

By analyzing the relationship between groundwater exploitation, changes of groundwater table, and development of land subsidence in history, it is found that: (ⅰ) in the period of 1956—1981, groundwater table declined gently for little groundwater exploitation, while the land subsidence also increased smoothly, (ⅱ) from 1989 to 2000, more groundwater was pumped rapidly and water table declined in great extent, accordingly, the land subsidence turned into instant development, and (ⅲ) from 1989 to 2000, groundwater exploitation and decline of water table slowed down, but the land subsidence was still in rapid expansion for the delay between water table decline and land subsidence. In general, the groundwater exploitation and water table decline match temporally the land subsidence in Taiyuan City.

Temporally, the groundwater depression cones are consistent with the land subsidence centers. The groundwater depression cones occur in Xizhang sub-zone and City sub-zone. They are the Xizhang groundwater depression cone in Xizhang sub-zone, and the groundwater depression cones of Wanbolin, Xiayuan, Wujiabao, and Beiying in City sub-zone. Accordingly, the land subsidence centers also occur in Xizhang sub-zone and City sub-zone. They are Xizhang land subsidence center in Xizhang sub-zone, and the land subsidence centers of Wanbolin, Xiayuan, and Wujiabao in City sub-zone.

It is suggested that the land subsidence in Taiyuan City is caused mainly by over withdrawal of groundwater in mid-deep aquifers. In addition, the development of land subsidence lags behind groundwater depression for the delay between water table decline and land subsidence.

(3)*Effect of strata characteristics and geological structures on temporal patterns of the land subsidence*

The monitoring data in the period of 1956—2000 shows that the land subsidence spatially coincides with the groundwater depression on the whole, but deviates locally. Firstly, the groundwater depression cone doesn't coincide exactly with the land subsidence center. Secondly, the amount of groundwater depression is disproportional with the land subsidence. At last, the land subsidence is localized in the alluvial plain, not emerging in the flood plain. In the present study, spatial heterogeneity of medium was used to explain the phenomena. The following factors were taken into account: patterns of accumulated clay soil thickness, configurations of clay soils and coarse soils, and mechanical properties of soils in different subzones and depths. It is found that the strata heterogeneity affects spatial pattern of the land subsidence in Taiyuan City.

The compaction occurred mainly in the clay interbeds and adjacent confining clay layers when groundwater level decreased. It means that the difference of clay thickness becomes the main factor affecting variation of subsidence volume under the same other conditions. Where the total clay thickness is greater often occurs greater compaction. Comparing the land subsidence contour maps with the clay thickness contour maps, we found the land subsidence centers in Xizhang sub-zone, Wanbolin sub-zone and Xiayuan sub-zone deviate from the corresponding groundwater depression centers to the sides in the east, south and west respectively, where there are thicker accumulated clay soils.

Under the same intensity of groundwater withdrawal, the subsidence volume is usually greater where clay interbeds are more and the individual interbed is thinner. If there are a lot of thin clay interbeds in formations, water can be drained off through the both sides or in different directions. In this case, when groundwater head decreases, the clay interbeds drain quickly, the time-delay between drainage and soil compaction is comparatively short, and subsidence volume is great accordingly. On the contrary, if there are few but very thick clay layers, drainage will be slow, the time-delay will be long, and subsidence volume will be small. In Wujiabao sub-zone, with a lot of thin clay interbeds in formations, the subsidence volume is the greatest though the groundwater depression isn't the greatest. And for Beiying sub-zone, with the much thicker but less clay layers, the subsidence volume is small because water is drained off very slowly. In Xizhang sub-zone, where the individual interbed is thin but the accumulated thickness of clay interbeds is small, the subsidence volume is comparatively small though the groundwater table declined greatly. In Wanbolin-Xiayuan sub-zones, where there are clay layers more than that in Xizhang sub-zone but less than that in Wujiabao sub-zone and the accumulated thickness is greater than that in the both sub-zones, the accumulated subsidence volume is greater than that in Xizhang sub-zone but much less than that in Wujiabao sub-zone.

According to the data from 32 drills in Taiyuan city, the statistic values of physical mechanical characteristics in different sub-zones were gotten. The sand layers in Xizhang and Urban sub-zones is the densest, in Beiying, Wanbolin and Xiayuan sub-zones looser, in Wujiabao sub-zone the loosest. Of the compressibility, the sand layers in all sub-zones are mid-compressible, though with the relative smaller in Wanbolin and Xiayuan sub-zones, the similar in Xizhang, Beiying, and Urban sub-zones, and the relative large in Wujiabao sub-zone. Of the liquidity index, the clay in Xizhang sub-zone has the minimum liquid limit value, the middle in Wanbolin, Xiayuan, and Urban sub-zones, and the maximum in Wujiabao sub-zone, with part of clay in soft plasticity static. Therefore, the maximum subsidence volume occurred in Wujiabao sub-zone can be partly attributed to the relative large compressibility and liquid limit value, while the less subsidence volume represented in Xizhang, Urban, and Beiying sub-zones partly can be attributed to the relative small ones.

In General, strata heterogeneity has the following effects on spatial pattern of land subsidence in Taiyuan City: (ⅰ) the land subsidence centers deviate from the corresponding groundwater depression centers to the sides with thicker accumulated clay soils, (ⅱ) in the same intensity of groundwater withdraw, the subsidence volume is usually greater where clay interbeds are more and the individual interbed is thinner, and (ⅲ) the land subsidence is correlated closely with the mechanical property of soil.

Additionally, tectonic process plays a more important role in causing land subsidence than what was thought before. The spatial distribution of land subsidence and geological structure were compared. The important findings are as follows: (ⅰ) all of the four land subsidence centers were close to the SN buried fracture line in central Taiyuan, (ⅱ) the centers were just in three geologically subsiding sub-zones, and (ⅲ) the axial directions of the centers were roughly parallel to directions of the structural lines nearby. The results indicate that there are three controls of tectonic movement on land subsidence: the first is to supply basin sediments; the second is the differential subsidence or vertical subsidence due to basin extension, and the last is its restriction on the location and expansion of land subsidence. For example, located in the Chengbei depression and restricted by Sangei uplift to the south, land subsidence center in Xizhang sub-zone is trending to expand to the north. Land subsidence centers in Wanbolin sub-zone and Xiayuan sub-zone lies in Urban depression and restricted by Sangei uplift to the south. For the special arrangement, clay thickness, and engineering mechanics properties of strata, land subsidence center in Wujiabao lies in Qinxian uplift, and expands to the south and north, where there are depressions.

(4)*Mechanism of land subsidence in Taiyuan City*

Undisturbed soil columns were sampled from the Wujiabao land subsidence center to carry out consolidation experiment under high pressure. The results suggest that: (ⅰ) land subsidence caused by groundwater withdrawal is essential for the changes of structure and physical mechanics properties of soil. In the process of pumping→tranquilization→recharging, the change of effective stress and land subsidence (soil compaction and rebound) delays behind groundwater table change, (ⅱ) clay has the nature of shrink when dehydration and swell when absorption and the nature varies for different types of clay, which causes that land subsidence centers are not always inaccordance with the groundwater cone, (ⅲ) in the process of land subsidence, decrease of pore groundwater stress is consistent with increase of effective stress, and dissipation of pore groundwater stress decides the velocity of land subsidence, and (iv) in the process of pumping→tranquilization→recharging, soil layer is in loaded-unloaded, and its rebound coefficient decreases when load increases.

(5)*Simulation, prediction, and control of land subsidence in Taiyuan City*

Through affecting compaction of each compressible layer, distribution of clay interbeds in formations has great effect on the spatio-temporal pattern of land subsidence which is the overall result of subsidence of all compressible layers in formations. When layered monitoring data of land subsidence is unavailable, determining the horizontal distribution of compression of individual compressible layer is important for spatial planning of groundwater exploitation. It has been well known that distribution of clay interbeds in formations has great effect on the spatio-temporal pattern of land subsidence. In this works, a modular subroutine of MODFLOW called Interbed Storage Package-1 was employed to simulate the horizontal distribution of subsidence in different compressible layers in Taiyuan City. Our results show that clay layer 3, clay layer 1 and 2, and clay layer 4, 5, 6, and 7 contribute chiefly to the land subsidence in Xizhang sub-zone, Wanbolin and Xiayuan sub-zones, and Wujiabao and Xiaodian sub-zones, respectively. It is suggested that both temporal and spatial arrangement of pumping wells must be taken into account to control land subsidence in Taiyuan. Pumping from middle water-bearing zone in Xizhang sub-zone and from the lower water-bearing layer in Wujiabao and Xiaodian sub-zones should be avoided. To control land subsidence in Taiyuan, both temporal and spatial arrangement of pumping wells must be taken into consideration. In Xizhang sub-zone, pumping from middle water-bearing zone should be avoided since the zone is adjacent to and partly contains clay layer 3, which is the major contributor to land subsidence in Xizhang sub-zone. In Wujiabao and Xiaodian sub-zones, the zone with the maximum land subsidence in Taiyuan, the pumping from lower water-bearing layer should be avoided for clay layer 4, 5, 6, and 7 that are the major contributors to land subsidence here.

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