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Analysis of Factors in Land Subsidence in Shanghai: A View Based on a Strategic Environmental Assessment

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Abstract: It has been observed that in the urban center of Shanghai, land subsidence has accelerated, and the groundwater level has continued to drop even though the net withdrawn volume (NWV) of groundwater has remained unchanged since 1980. An analysis of monitoring data shows that drawdown of the groundwater level is one of the factors that have influenced land subsidence since 1980. The NWV of groundwater in urban areas, however, is not the critical factor controlling the drawdown of the groundwater level. Since the 1980s, there have been many underground works constructed in the unique strata of Shanghai, which has an interlayered structure known as a multi-aquifer-aquitard system (MAAS). Investigation into land subsidence caused by urban construction is now receiving much attention. Based on the principle of a strategic environmental assessment (SEA) for sustainable urban development, this paper presents a discussion and analysis of the factors which can influence the development of land subsidence during continued urbanization in Shanghai. The main factors include the additional loading caused by the construction of structures, the cut-off effect due to construction in aquifers, the drawdown of groundwater level caused by leakage into underground structures, and the decrease of groundwater recharge from neighboring zones. SEA is recommended for the future development of Shanghai.

Keywords: land subsidence; groundwater; urbanisation; strategic environmental assessment

1. Introduction

Groundwater is the most important resource which is extracted worldwide for irrigation, industry, and domestic use. Much research is conducted into maintaining sustainable levels of groundwater extraction [1–3]. In Shanghai, groundwater pumping started in the early 1860s, and it has resulted in serious land subsidence [4–7]. The average cumulative subsidence as of 2009 in the urban area has reached 1.97 m [6]. Since 1966, measures relating to groundwater control have been adopted (such as banning unnecessary groundwater withdrawal, changing the withdrawal source to deeper aquifers, and adopting artificial recharge [7,8]). With these measures implemented, land subsidence was controlled for a period of time. However, since the 1990s, land subsidence has again increased.

With the rapid expansion of urban development since the 1990s, a significant amount of municipal infrastructure, such as water supply, gas pipelines, electric transmission lines, metro lines, underground structures, and high-rise buildings, has been constructed. Environmental sustainability has become a focal point in urban development [9,10]. Urbanization seriously affects the natural environment, not only in terms of environmental pollution, but also in the deterioration of the geological environment, which can induce geohazards.

As depicted in Figure 1, the multi-aquifer-aquitard groundwater system (MAAS) in Shanghai consists of a phreatic aquifer group (Aq0) and five confined aquifers (AqI–AqV), which are divided by six aquitards (AdI–AdVI) [11–13]. The phreatic aquifer group, Aq0, has two secondary types: one is the phreatic aquifer (Aq01) and the other one is the artesian aquifer (Aq02). Bedrock outcrops have a total area of about 2.5 km^2, and are generally distributed as separate mounds. The remaining bedrock is primarily covered by Quaternary sediments and is also partially covered by Tertiary deposits 300 m in thickness. The foundation-bearing soil strata and underground construction depths are generally within a 100 m depth [11,13]. The presence of these underground structures will change the hydrogeological characteristics of the strata and aquifers. Some researchers have accepted that urban construction is now a significant factor for land subsidence [12,13]. The proportion of subsidence caused by construction in the urban area is thought to be more than 30% of the overall land subsidence [13]. However, the mechanism by which urban construction can accelerate land subsidence in Shanghai has still not been adequately explained.

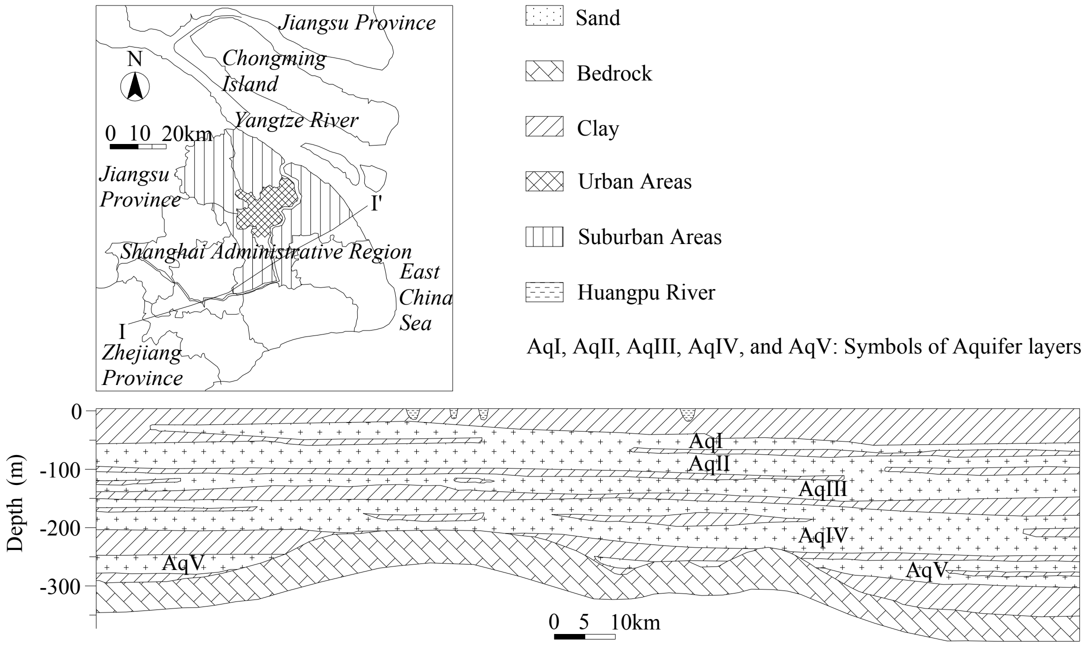

Figure 1. Shanghai hydrogeological profile (cross-section I–I′) and location of urban areas.

As increasing subsidence can affect the normal operation of municipal infrastructure, the municipal government has published a "Shanghai decree" to prevent and control land subsidence so that the sustainable development of the city can be ensured [14,15]. However, the effectiveness of this decree needs to be examined. It is necessary to verify whether the environmental impact assessment (EIA) should be at the project level or at the level of SEA [16]. SEA, which takes the environmental impact of policies, plans, and programs (PPPs) and their alternatives into account, is generally recommended in EIA [17].

The objective of this study is (i) to provide a scientific assessment of the relationship between land subsidence and constructed facilities based on data; (ii) to investigate the long-term mechanisms leading to increasing subsidence; and (iii) to protect the geological environment based on the SEA level. The term "environment" used in this paper specifically relates to the geological environment in which the geohazards of land subsidence can arise. To ensure the sustainable development of Shanghai, decision-making concerning PPPs must be based on SEA in the future.

2. Methodology

2.1. Data Extraction

The land subsidence monitoring system includes monitoring of land subsidence levels and soil deformation, and monitoring of the groundwater regime, and is supervised by the Shanghai Institute of Geology Survey (SIGS). All data on land subsidence, soil deformation, groundwater levels, and groundwater withdrawn volume were extracted from the records of the SIGS. The land subsidence data were extracted from the land subsidence level monitoring network in Shanghai. The area covered by this network includes the entire administrative region of Shanghai. The distance between each leveling point is about 0.5 km in the urban center [14,18]. The leveling is checked against GPS survey data to ensure the accuracy of the land subsidence data. All of the soil deformation data were extracted from soil deformation monitoring stations, each one consisting of a bedrock benchmark and borehole extensometers, which have been installed for decades, to form the soil deformation monitoring system [18,19]. The benchmarks are protected by high-quality thick seamless steel tubing, and cement mortar has been grouted into the joint between the boring holes and the steel tubes. Mineral exploration theory and techniques were applied to design special borehole structures to convert the elevations of formations at different depths to the ground level for correlating measurements. In this way the monitoring stations can reflect the soil deformation at different depths. The data for groundwater levels and groundwater withdrawn-recharged volume were extracted from a groundwater regime monitoring network. The positions of groundwater level monitoring boreholes and the borehole extensometers correspond to each other. All of the data on urban construction, including the distances of metro lines from the operational floor area of buildings, were extracted from the archives of the Shanghai Statistics Bureau (SSB) [20].

2.2. Data Analysis

Once the land subsidence data for each monitoring point had been extracted, they were treated as a sample of a population [16]. Generally, within any monitoring data sample, there are some abnormal data which have been caused by systematic errors and observation errors, and so the Grubbs test method was used to identify and eliminate the abnormal data [17]. For a random sample of n items, a parameter T_i is expressed as follows

$$T_i = \frac{x_i - \overline{x}}{s} \tag{1}$$

where, $\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$, $s = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2}$, and x_i is an observation selected arbitrarily from the sample.

Once T_i is equal to or greater than the limit $T(n,\ \alpha)$, which can be found in a Grubbs' table, according to sample number (n) and confidence limits (α), x_i is deemed to be abnormal data which should be eliminated from the sample [21–23].

Testing to determine the deviation from the sample average value was done to identify data samples from the urban center and the suburbs, based on the t-distribution method [24]. For two samples of n_1 and n_2 items, respectively, a parameter t is expressed as follows

$$t = \frac{|\overline{x}_1 - \overline{x}_2|}{s\,(\overline{x}_1 - \overline{x}_2)} \tag{2}$$

where $\overline{x}_1$, $\overline{x}_2$ = average value of Sample 1 and Sample 2; $s^2\,(\overline{x}_1 - \overline{x}_2) = \frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{(n_1-1)+(n_2-1)}$, s_1, s_2 = standard deviation of Sample 1 and Sample 2.

Once t is lower than the limit $t(f,\alpha)$, which can be found in t-distribution tables, according to degrees of freedom (f) and confidence limits (α), Sample 1 and Sample 2 are deemed to come from one population.

An analysis of the average subsidence in the urban center was then carried out based on a triangulated irregular network (TIN) by considering the distribution density of monitoring points [19]. Each triangular shape in the TIN is formed by the shortest lines between two monitoring points. The area average subsidence in the urban area can be expressed as follows:

$$\Delta h = \left(\sum S_i \cdot \Delta h_i\right) / \sum S_i \tag{3}$$

where Δh = the area average subsidence; S_i = the area of each triangle in the TIN; and Δh_i = the average subsidence of the center of the circle around each triangle.

3. Results

3.1. Increase in the Subsidence Rate since 1989

From 1921 to 1965, land subsidence and the net withdrawal volume (NWV), which equals the groundwater withdrawal volume minus the groundwater recharge volume, both increased annually in the urban area [4,7,8,10,25]. Since 1966, some measures related to groundwater control have been adopted, such as the banning of unnecessary groundwater withdrawal, changing the withdrawal source to deeper aquifers, and adopting artificial recharge; additionally, land subsidence has been controlled within a small region [26]. However, after 1989, land subsidence increased again. Figure 2 shows the variation in average cumulative subsidence in Shanghai since 1966, with elapsed time in years. For comparison, the variation in the total building floor area which is defined as the sum of the area of all the floors of all the buildings is also plotted in Figure 2. As depicted in Figure 2, the annual rate of land subsidence during each period reached 3.84 mm/year in 1980–1989 (v_{s1}), 9.97 mm/year in 1989–1995 (v_{s2}), and 12.09 mm/year in 1995–2005 (v_{s3}), while the rate of increase in floor area was 0.58×10^6, 2.30×10^6, and 13.17×10^6 m^2/year, respectively [5,26]. The values of v_{s2} and v_{s3} are more than two and three times v_{s1}, respectively, so that even if the annual net withdrawn volume had decreased, land subsidence still accelerated during the 1990s. A regression analysis was carried out taking account of three main parameters: the floor area, the length of the metro lines, and the cumulative subsidence.

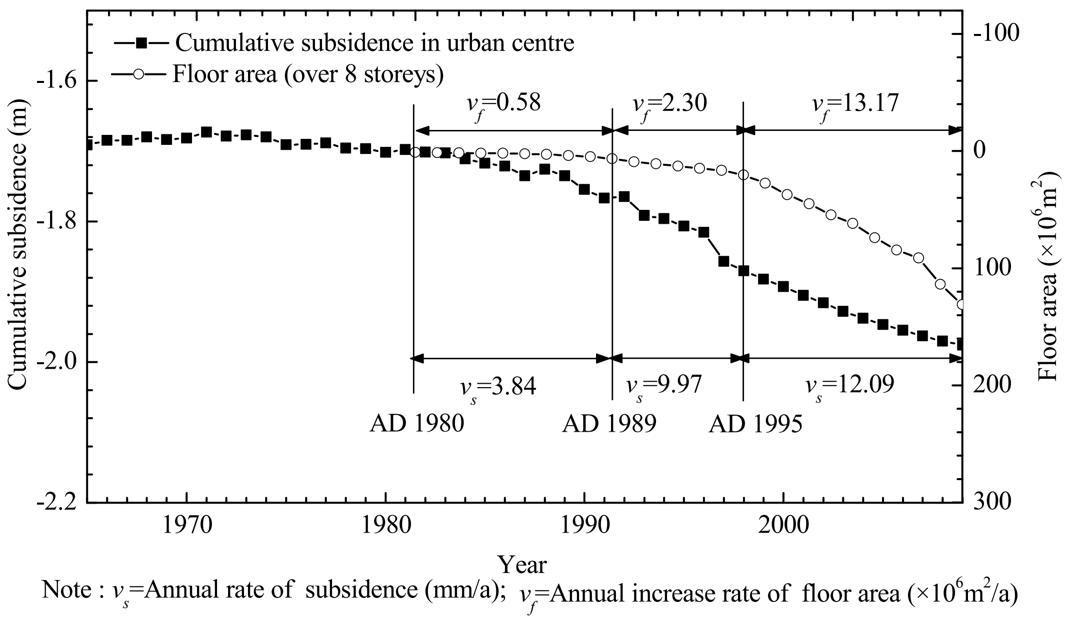

Figure 2. Relationship between floor area and cumulative subsidence (based on Reference [25]).

3.2. Subsidence and Groundwater Withdrawal

The relationship between the average cumulative land subsidence and the cumulative NWV of groundwater in the urban center is shown in Figure 3. Until 1979, the graphical relationship between the cumulative land subsidence and the NWV is almost linear. During this period, the increase in land subsidence corresponded to the increase in the net withdrawn volume. However, a shift occurred around the year 1979. From 1980, since the annual recharged volume of the groundwater has been greater than the withdrawn volume, the cumulative NWV has decreased. Even when the NWV was decreasing, the rate of land subsidence began to accelerate rather than decrease, as had been the case in the preceding period. If the NWV exceeded the critical value, it would show no correlation with the variation in land subsidence in the urban area.

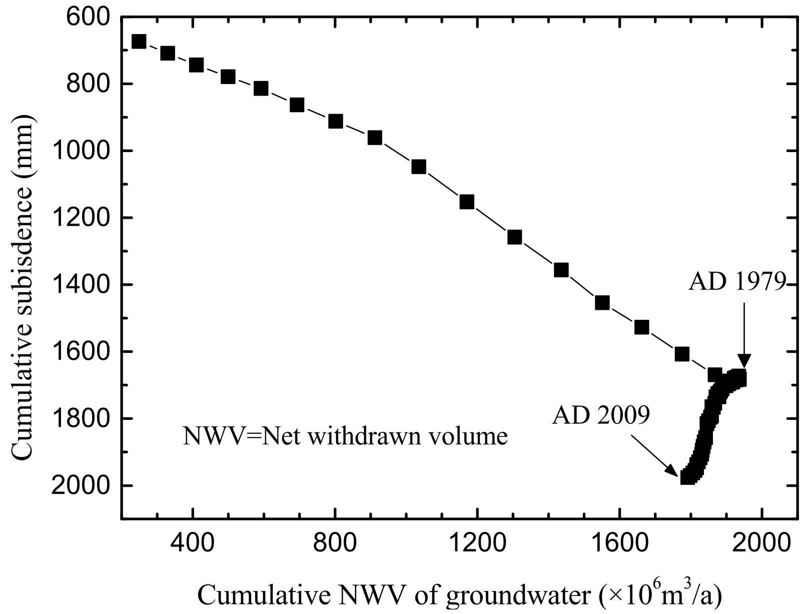

Figure 3. Comparison of cumulative land subsidence and NWV of groundwater (based on Reference [25]).

The cumulative land subsidence and the detected piezometric level in AqII, AqIII, and AqIV since 1980 are compared in Figure 4, respectively. According to the results of a regression analysis, each group of data shows a clear relationship between the cumulative subsidence and groundwater level. The correlation coefficients are 0.95 for AqII, 0.95 for AqIII, and 0.99 for AqIV. The increases in cumulative subsidence in AqII and AqIII are more sensitive to the change in the groundwater level than that in AqIV. As recorded in a similar situation in the Hong Kong region, a possible reason is the cut-off effect caused by underground structures [27,28]. Where this effect is present, land subsidence correlates more with the decline in the groundwater level than with the NWV.

This analysis implies that the groundwater level may be the most critical factor that controls land subsidence and therefore it is important to study the reasons for the drawdown and the mechanism of continuous drawdown of the groundwater level in the urban area.

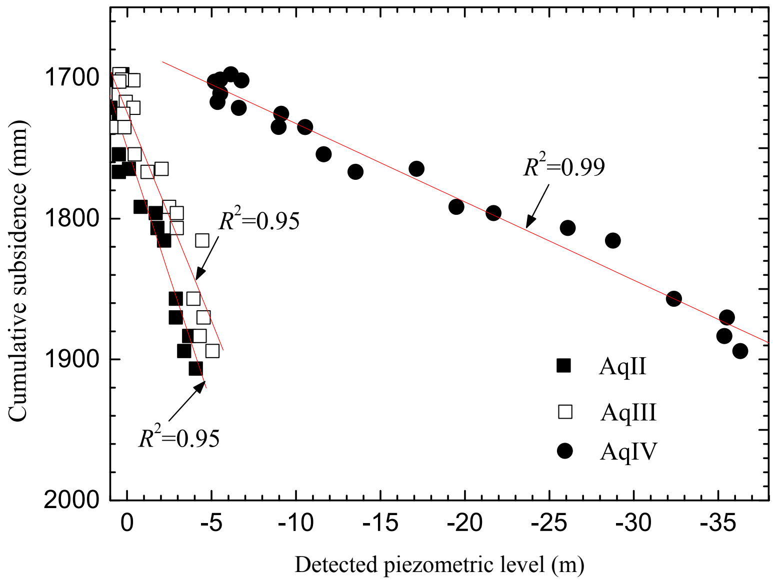

Figure 4. Comparison of cumulative land subsidence and detected piezometric level in each aquifer since 1980 (based on Reference [25]).

3.3. Subsidence and Urban Construction

Comparing the change in building area in Shanghai and the average cumulative subsidence in the urban area, a regression analysis was performed as shown in Figure 5. As a result of the regression analysis, an exponential curve with a correlation coefficient of 0.997 can be drawn. The relationship between the total length of the metro lines in operation and the average cumulative subsidence (see Figure 5) has similar characteristics, with a correlation coefficient of 0.972 obtained by regression analysis, which indicates that the length of the metro lines in operation, as well as the total floor area, contribute to the accelerated land subsidence. However, before 1980, there is no correlation between either the floor area or the length of the rail track in the metro system and the cumulative subsidence. Based on this regression analysis, the construction of urban infrastructure such as metro lines has become an important factor contributing to further land subsidence since 1980 in the urban area.

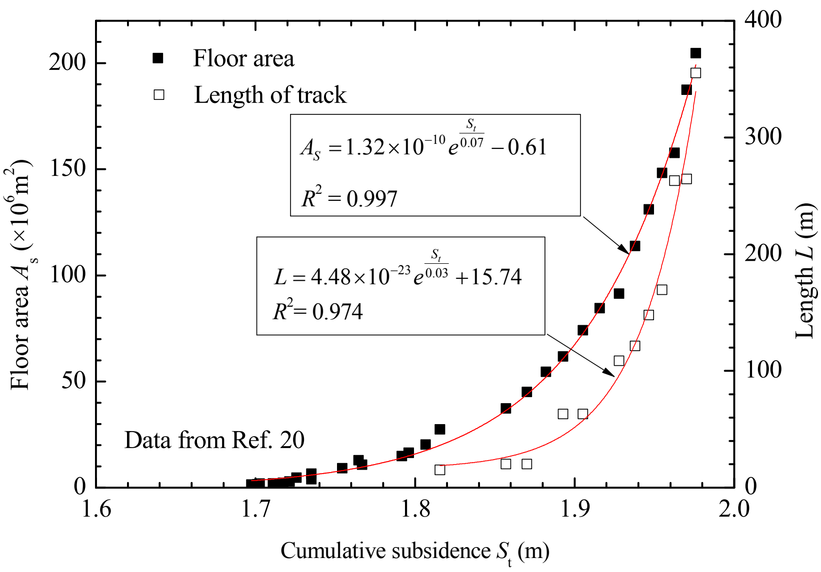

Figure 5. Regression analysis of floor area, total length of track in operation and cumulative subsidence.

According to the above analysis, cumulative land subsidence in Shanghai urban areas is correlated with the construction of structures. The relationship between the total floor area or the total length of the metro lines and cumulative subsidence fits exponential functions with high values of correlation coefficients.

4. Discussion

4.1. SEA Principle

Shepherd and Ortolano [16] summarized the following six principles for SEA effectiveness in promoting sustainable urban development: (1) considering the sustainability principles integrally and systematically; (2) assessing projected environmental impact on the urban area due to policy plans and construction; (3) considering multiple and correlated impacts comprehensively; (4) paying more attention to the sustainability principles of projects rather than PPPs; (5) monitoring and adopting measures to improve environmental management; (6) perfecting legal and public monitoring mechanisms.

In order to mitigate the risk to the environment, the Shanghai municipal government published a decree to prevent and control land subsidence [15] (referred to in this section as the Shanghai decree). In this decree, an environmental impact assessment (EIA), particularly considering the effect on land subsidence, must be conducted for certain construction projects, such as significant municipal projects, where the depth of excavation is over 7 m, and for construction projects within a high subsidence region. The evaluation is started during the planning of the project, and includes an expert evaluation program for the construction project prior to its start on the site. However, on completion of the construction project, the EIA is ended. In order to check the EIA level of the Shanghai decree, six principles of the SEA are applied to quantitatively examine the Shanghai decree. As shown in Table 1, only 16 out of a total of 30 points are met under the Shanghai decree. Most of the principles are just partially considered in the Shanghai decree and there is no public involvement. Therefore, this decree is still based on the principle of EIA at the project level [17], rather than at the SEA level. To ensure sustainable urban development [17,29,30], SEA takes the environmental impacts such as policies, plans, and programs (PPPs) and their alternatives into consideration simultaneously [15,16].

Table 1. Shanghai land subsidence decree *vs.* SEA six principles.

SEA Principle	Establishment of Shanghai Land Subsidence Decree	Score out of 5
1	Not perfect: there is no integrated framework for considering sustainability principles.	2
2	Not perfect: mostly considered before the projects start.	3
3	Not perfect: many factors are not considered for the cumulative impacts.	2
4	Need to ensure sustainability principles extend down to projects.	3
5	Yes: monitoring of environment during construction. However, during operation, no groundwater level monitoring.	4
6	No public involvement or appraisal.	2
Note:	If SEA principles are fully adhered to, a full score of 5 is awarded for each principle; the total score following SEA principles is 30.	16

4.2. Factor Identification Based on SEA

Based on SEA, the factors influencing land subsidence in Shanghai induced by urbanization are summarized as follows: (i) additional load, involving building load and dynamic load; (ii) underground structure construction, involving construction of tunnels and foundation pits; and (iii) drawdown of groundwater level in the long term, possibly caused by leakage in tunnels and reduction of groundwater replenishment.

4.2.1. Additional Load

To date, most research has concentrated on additional building loads which result in land subsidence. Since 1980, the number of high-rise buildings with pile foundations has exceeded 1000. When the pile length reaches 45 m, piles will have reached AqI, and if the length is from 60 m to 90 m, piles will have reached AqII. In order to analyze the effect of additional stresses due to building loads, Tang *et al.* [31] conducted a model test which considered the influence of high-rise buildings. Jie *et al.* [32] found that the increase in land subsidence is highly correlated to the rate of development of urban construction, and involves the distribution density of buildings, the regional scale of construction, and the construction speed. The distinctive soft deposits in Shanghai have high compressibility, long-term primary consolidation and sensitivity to additional load. Xu *et al.* [26] surmised that the maximum final settlement of a high rise building in the urban center is about 50–100 mm, which is related to the characteristics of the soil and the type of pile foundations.

Dynamic loads caused by the construction of pile foundations and traffic loading are also a factor in land subsidence. When the seismic wave due to pile driving travels through the ground, deformation of the strata will occur due to the compression of soils. Jongmans [33] suggested that an influence radius of 50 m should be considered during pile driving. There can also be an additional load from embankment construction during urbanization [34,35], and cyclic loading due to traffic can also lead to the deformation of strata. According to an investigation made by Ling *et al.* [36], traffic loading at an intersection of the Shanghai outer ring road could result in a residual settlement of 50 mm. Wu *et al.*'s results [37] showed that the influential depth in the subsoil, in the soft Shanghai deposits, due to train vibration was around 4.5 m, and the maximum residual settlement from train vibration is about 20 mm.

4.2.2. Ground Disturbance

Underground construction processes, such as the excavation of foundation pits, can cause disturbance of strata and lead to the deformation of surrounding layers. In addition, ground disturbance caused during the construction of tunnels may continue to have an effect on settlement for a long period of time. After the operation of Metro Line No. 1 for 15 years, the annual differential settlement of the tunnels was still significant. The average settlement was about 30 mm per year, but at one stage the maximum value of cumulative subsidence reached 350 mm within one year [38].

The effects of foundation pit excavation on land subsidence have become more apparent in recent times [39,40]. In order to maximize the use of underground space, excavations have become deeper and larger. In Shanghai, excavation is generally done using the well-point dewatering method, which can lead to the depression of the groundwater level with the withdrawal of groundwater. This can result in the influence radius of land subsidence being as much as 15 times the excavation depth. Based on engineering practice, the influence radius of dewatering in a foundation pit is about 130–180 m, and for every 3.5 m reduction in groundwater level, there is 5–15 mm of ground settlement [39].

4.2.3. Long-Term Drawdown of Groundwater

Figure 3 shows that annual NWV, decreasing since 1980 in the urban area (marked in Figure 1), gradually becomes a less critical factor influencing the drawdown of the groundwater level. However, the drawdown of the groundwater level is still a major factor for land subsidence in the urban area as shown in Figure 3. The potential factors for the drawdown of the groundwater level which arise during the process of urbanization are as follows:

(i) the increase of NWV in the suburban area; (ii) the cut-off effect of underground works on the recharge of groundwater from the suburban area to the urban area; (iii) the leakage of groundwater into metro tunnels.

When the drawdown of groundwater was the result of pumping in the urban area, groundwater in the suburban area flowed to the urban area as recharge. In the early period, the NWV in the urban area was much higher compared to that in the suburban area. However, the main region of groundwater withdrawal gradually moved to suburban areas in the 1970s. The ratio of the volume of groundwater withdrawn in urban areas to that in suburban areas was 1:70.7 in 1970, compared with 8:1 in 1949, and 1:0.98 in 1964. Thus, the groundwater in urban areas lost recharge from suburban areas.

The cut-off effect of existing underground structures, which can influence the seepage of groundwater in aquifers, is another important reason for the reduction in recharge from suburban areas to urban areas. For example, structures acting as diaphragm walls can hinder the groundwater flowing in aquifers. Also, because of existing underground structures, groundwater in a hydrostatic pressure condition may change into a condition with an unsteady downward flow. Because of the cut-off effect of underground works, the steady flow in aquifers changes into turbulent flow, which makes the groundwater head around the bottom of underground structures lower than that around the top [41–43].

The shield method is widely adopted in the construction of Shanghai metro lines. Usually, the lining in the metro tunnel consists of six segments, which means there are a lot of joints throughout the tunnel. Field investigations have found that groundwater leakage occurred frequently in joints and cracks in segments and grouting holes [44–46]. During the initial period of construction, the volume of groundwater leakage and the deformation of the tunnel can be ignored. However, as the leakage is developing, deformation of the tunnel and further leakage caused by differential settlement perpetuate the process. Wu *et al.* [46] concluded that leakage in tunnels can cause a decline in the groundwater level and result in tunnel settlement. Leakage occurs not only in tunnels but also in deep excavation works [47–51]. However, the reduction in the groundwater level contributes more to land subsidence. It was concluded that the rate of leakage in Shanghai metro tunnels averaged 0.1 $L/m^2/d$ and the distribution of leakage locations was uniform along the tunnel. The expected magnitude of land subsidence in the region with tunnels was only about 40 mm after 10 years.

Therefore, the potential factors contributing to land subsidence in the urban area include the additional load caused by the construction of both above- and below-ground structures, well-point dewatering in the excavation of foundation pits, groundwater leakage in metro tunnels during construction and operation, and the reduction in groundwater recharge from the suburban area to the urban area due to the cut-off effect of underground structures, which is considered to be the main factor. Further research on the mechanisms of these factors causing land subsidence in the urban area of Shanghai is still required.

5. Conclusions

In general, based on SEA for sustainable urban development, the influencing factors which may lead to land subsidence during the urbanization of Shanghai are discussed. The conclusions are summarized as follows:

(1) Land subsidence in Shanghai is closely correlated to construction in the urban area. The correlation between cumulative subsidence and the building area is strong, as is the correlation between cumulative subsidence and the total length of the metro lines.

(2) The Shanghai decree for land subsidence control does not closely follow the principles of SEA to ensure sustainable urban development. Most of the principles are only partially considered in the Shanghai decree, and there is no public involvement in the Shanghai decree.

(3) The influencing factors resulting in increasing land subsidence in the urban area include additional load caused by construction, dewatering during excavation, groundwater leakage into metro tunnels, and the reduction in groundwater recharge from the suburban area to the urban area.

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