Land subsidence and water management in Shanghai

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Master’s thesis
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Abstract

Land subsidence is the lowering of the land surface elevation due to the compaction of soil. It is a geological event that is accelerated by man through a long term exploration of the ground sources, and they represent a disruption of a natural equilibrium. Land subsidence combined with a global sea level rise creates a serious environmental problem in the coastal region.

Land subsidence is an international hot issue now because it happens in lots of big cities. This thesis is about the land subsidence happening in Shanghai. It is a serious geology problem now. It results in permanent loss of ground elevation, lowers the standard of flood preventing establishments and increases the risk of natural disasters of typhoon, rainstorm, flood and astronomical spring tides. In summer, under the complex effect of land subsidence, river flood of Yangtze, local rainstorm, typhoon surge and annually high tide, the disaster of flood and waterlog can be very severe. Spatially, urban land subsidence occurs in active regions of economy and engineering and is consistent with distribution of heat island and rain-island. Therefore land subsidence is an important factor which can affect the city development in Shanghai.

It is very necessary to do some research on this subject because it not only leads to the loss of economic but also even people’ lives. In this thesis land subsidence is explained in details. The theory of land subsidence is discussed. The history data of land subsidence is used as a reference. The present measures are evaluated. The tendency of land subsidence is predicted and some suggestions are given on how to solve this problem in the future.

The main reason of land subsidence in Shanghai is the groundwater over extraction and it can also leads to some problems related to water. Because my major is Land and Water Resource Management it is suitable for me to do some research using the knowledge got from two years master study in TU Delft. I hope thesis can make people know more about land subsidence and some recommendations I give are useful for land subsidence prevention.
Biographical sketch

Quanlong Wei was born in Shandong Province of China on August 8th 1978. He grew up in this big country characterized by one of the human being's cradles.

His hometown is a poor rural area. Not enough water for irrigation in his home town made him suffered a lot during the child period. He decides to change the actuality by his effort. So he studied hydraulic engineering at Wuhan University in China. In 2001 he got his B.S. degree.

From 2001 to 2004 he worked in Jinan Water board in Shandong Province. He thinks what he learned is not enough. So he decides to finish master degree. The Netherlands is the best choice for him because of its long famous water management history. He selects the suitable university TU Delft as the next station. He has finished all the courses study now and after completion of his thesis he will receive his M.S. degree from TU Delft.
Acknowledgments

First, I would like to express my sincere thanks to Van de Ven, From the beginning to the end he gave me lots of help and encouragement. He is good at urban water management and he gives me lots of good ideas how to write this thesis. Nick van de Giesen gives me the general supervise and some good supports. Robert Verhaeghe and David Biron give me some good advices and comments about my thesis during the committee meeting. They are very friendly and patient for me. Jaap de Koning and Mw. Betty Rothfusz give me lots of helps during my study life in TU Delft.

I would like to express my sincere thanks to my friends Wangjun and Dong Bibo who is working in Shanghai Water Board for giving me some valuable data and technical support about urban water management and land subsidence. I am very grateful to Prof Gao Dazhao for the helpful discussions about my thesis.

Thanks for all the students who are studying in the same office with me for the time spent together.

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1 Introduction

Shanghai, as the most developed city, is facing to a big problem now. Land subsidence as a major and well-known geological hazard in Shanghai has caused serious losses.

Shanghai is one of three cities in the country that have sunk more than two meters since last century. The magnitude of land subsidence has reached to 2.63m in Shanghai downtown area from 1921 to 1965 because of groundwater overexploitation concentrated there. From 1959 to 1961, land subsidence was accelerated to a rate of 110mm/y. If no measure was taken from 1960, Shanghai should be under sea level now. The mean land level is between 3m to 4m above sea level in Shanghai, but the flood defense wall is more than 6m now. It is still not high enough with the sea level rising and land sinking. How serious the situation is now in Shanghai!

Great efforts have been taken to control land sinking. Some measures play good role on solving this problem. Artificial recharge makes up the shortage of ground water and retards the land sinking, but it is not enough. Ground water extraction plan is made every year. Using water in an efficient way is advocated. The government is trying to limit the height and density of new buildings constructed downtown. More and more new laws or regulations come out. All these measures make people even think that a bright future is coming about land subsidence control.

However the situation is not so affirmative. “It is not easy to stop the over pumping because the users of underground water exist everywhere from downtown to rural areas, the different governments often conflict when facing this problem” said Liu Shouqi of the Shanghai Bureau of Housing, Land and Resources Administration. “Although the current (subsidence) rate will keep the city above sea level for more than 300 years, it still holds several potential dangers” said Li Qinfen, a professor at the Shanghai Institute of Geological survey. It has already forced the city to raise its floodwall again and again. And
it will also very probably lead the city’s subway lines to deform because of the unevenness of land subsidence.

There is still a long way for Shanghai to put the problem under control well. More researches and measures should be done to improve the situation now.
2 Land subsidence in Shanghai

2.1 The city of Shanghai

Shanghai is a coastal city. It locates at the coast centre of China. Shanghai is the second biggest city in China. It is the economical and financial centre. It is also a port city. The Pacific Ocean is at the east of Shanghai. It also locates on the delta area of Yangtze River. It is a low land city in China. There are two big rivers flow through Shanghai. One is called Yangtze River and another is called Huangpu River. The main ground level is about 3~4m above sea level. On general the east part is higher than the west part. The total area of the city is 6340 km$^2$. The longest length from east to west is about 100km and from the north to the south is about 120km. The rivers and lakes area is about 532km$^2$. The total population is about 13.3 millions in 2002 which is 71 thousand people more than that of 2001. In 2005 the population reached 18 millions.

2.2 The geology and hydrology

2.2.1 Geology of Shanghai

The Shanghai area was under sea water about 3 million years ago. As a result of movements of the Earth’s crust, the area rose above the sea about 10,000
years ago. It is a flat area. It is a not only old but also young area. The base of the city is very old but the cover of the land is very young. Most of the covered soil is the 4\textsuperscript{th} century sedimentation whose depth is about 300m. But only the upper 75m depth of soil has closed relationship with the people's activities. The position selection of building depends on the soil type. On general from surface soil to the II pressed layer is the better natural building site or can burden the pressure of shallow site. The first and the second sandy layers are the pressure burden layers for the normal scale building peg site. The first aquifer and the III pressed layers are the pressure burden layer of the pile site for very high building.

According to the research the first 75m soil has much relationship with the land subsidence which can be seen on figure 2

<table>
<thead>
<tr>
<th>depth(m)</th>
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<th>soil type</th>
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<td>clay</td>
<td>surface soil</td>
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<td>45</td>
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<td>the I pressed layer</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="soil layers" /></td>
<td>muddy clay (with sand)</td>
<td>the II pressed layer</td>
</tr>
<tr>
<td>75</td>
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<td>hard clay</td>
<td>hard soil layer</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="soil layers" /></td>
<td>fine sand</td>
<td>the first aquifer layer</td>
</tr>
</tbody>
</table>

Figure 2 Soil layers underground of Shanghai

There are 5 confined aquifers within 300m depth from the ground which can be seen from the figure 3. The IV aquifer has more amount of groundwater than that of other aquifers.
2.2.2 Hydrology of Shanghai

The total water area (including river and lake) is 532km². The length of rivers is about 20 thousands km. The Huangpu River goes through the city. Its total length is 82.5km and the width is 300~700m. Yangtze River locates at the north part of Shanghai.

The mean rainfall is about 1162mm/year. On the whole the rainfall is not well-balanced in one year. But normally from the middle of June to the beginning of July it is called “Meiyu period”. During these 20 days the rainfall is about 200mm. During the flood period (June~September) the rainfall is more than 600mm. The following figure is the rainfall map per year for Shanghai.
The mean temperature for the whole is about 16.8\(^{\circ}\)C. The highest temperature is about 38.8\(^{\circ}\)C and the lowest temperature is about -3\(^{\circ}\)C.

### 2.3 The necessity research on land subsidence

Urban water management in this city is becoming a big problem with the increase of the population. Land subsidence caused by groundwater use leads to lots of losses and makes many buildings more and more dangerous. Because of its importance the government decides to give more attention to this problem.

Land subsidence is not a new problem for Shanghai. Lots of damages and losses have happened because of land subsidence in Shanghai. Most of the people think that the land subsidence is nothing with their daily lives. But some experts indicate that it is not the case. From the short view it can affect our transports and safety. For example the tunnel of the subway can deform easily because of the unbalanced land subsidence. This can lead to the tunnel sinking and leaking which can endanger the safety of the surrounding buildings.
For a long view with the increasing temperature of the earth the sea level will increase either. It is estimated that on 2050 the sea level near Shanghai will increase about 6cm. If the land subsidence can not be controlled properly the mean ground level of Shanghai will be lower than sea level after 40 or 50 years. Figure 5 shows the ground level of different places in Shanghai.

![Figure 5 Ground level of Shanghai](image)

According to the record, the subsidence of the land in Shanghai can be seen clearly in figure 6.
From figure 6 we can see that the land subsidence is large before 1963 the Maximum value is about 110mm/year. In the figure the negative value means that the recovery of the land level. Table 1 shows us the three important periods for the land subsidence from 1921 to 2001.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>mean subsidence (mm/y)</td>
<td>39.1</td>
<td>3.4</td>
<td>12.8</td>
</tr>
</tbody>
</table>

Table 1 Land subsidence between three different periods

Land subsidence is a slowly-caused geological calamity whose emergency and development is not easy to be detected. It gradually made the environment more and more dangerous by the permanent lower down of the ground elevation. Land subsidence effect is accumulative and it can lead to damage suddenly. It plays an important negative role in the urban development.

Land subsidence leads to the permanent lower down of the ground elevation, changes the physical condition of earth surface, and forms subsiding depressions in the center of the city. These would put heavy pressure on the
flood control system, which were the most important aspects of the influence caused by the land subsidence.

![Figure 7 Spatial variations in grade of land subsidence in Shanghai](image)

According to the annual ground level measurement, land subsidence occurred almost everywhere on the 6340km$^2$ area of Shanghai, with a various velocity and the maximum at the center. It can be divided as four regions according to the different land subsidence velocity from 1921 to 2001 (figure 7). Region I have the quickest subsidence velocity, about 10-13mm/year; region II is the comparatively quicker, with an averaged velocity about 5-10mm/year; region III have the medium subsidence velocity, about 3-5mm/year; region IV has slower velocity, about 1-3mm/year; Region V is a basically stabilized region whose average velocity is less than 1mm/year.

Now in the center of the city, the ground elevation is between 2.2 and 4.5, lower than the natural level, which is 4.5m to 5m. The area which the elevation is lower than 4m, 3.5m, and between 3.0 m and 2.5m is 1069km$^2$, 11km$^2$, 6km$^2$ respectively.

From the information we can know land subsidence is not a neglected problem. If we do not take some measures or research on it Shanghai will have a disaster in the coming future.
2.4 The harm of land subsidence

2.4.1 Flood defense affected by land subsidence

Shanghai is the delta area of Yangtze River. She is at the outlet of the Yangtze River and downstream of Taihu basin. There are all kinds of weathers changing during the year. On general the land is flat in Shanghai. She is a lowland city. Flood defense is very important for the whole city. Before 1920s the mean land level is about 4m. Because a large amount of water was pumped out of the ground every year, from 1921 the ground level went down gradually. The total mean subsidence is about 1.76m. The ground level is 2m lower than the flood defense standard in Huangpu River. Now if there is a storm or tide the water level in river is more than 4m, so land subsidence has caused big problems for the flood defense in Shanghai.

As an important flood discharge river, Huangpu River released 80% of the water discharge of Taihu basin. Precipitation mainly happens in summer in Shanghai city and summer is also the flood season in Yangtze River basin and Taihu basin, the Huangpu River is easily being suffered by the flood disaster in summer. Land subsidence lowered the standard of flood control works, weakened the flood defense ability and brought heavy pressures on the flood control situation. It makes the water level in the river higher correspondingly. In some location of Shanghai the river becomes “the hanging river above the ground” which often leads to overflow from the dyke. Some pumps in pumping stations have to be stopped. This can early lead to the city flooded.

The land subsidence aggravates the flood control situations and the calamity process together with the meteorological disaster. In 1962 the high tide level was about 4.94m. There were 46 locations which were damaged along the dyke. Almost all the cars and buses can not run in the street. Water stayed in the city for more than ten days. Half of the city was flooded. The deepest water depth in the street was about 2m. There was about 50 million euros lost during this flood. The main reason for the flooding is the land subsidence which makes some low-lying area in the city. From 1921 to 1962 there is about 1.53m
land subsidence. During 6 years (1956~1962) the ground level goes down about 0.57m. This makes the flood defense wall higher and higher correspondingly.

Land subsidence deteriorates flood prevention situation through knocking down the ground elevation which directly knocks down the standard to defense and increase the devotion about engineering construction. With the accumulating of sedimentation, the situation influenced becomes worse and worse, land subsidence makes great changes on Shanghai region and landform. Original elevation of ground in downtown is about 4.0-4.5m, but now is less than 3.5m; some parts are less than 3.0m. High-tide level of the bund along Huangpu River is 3.22m, which result in overflowing, backing up of flood prevention wall and cloudburst flooding.

Figure 8 shows the relation between the land subsidence and the flood defense in one location of Huangpu River. On one hand the ground level becomes lower and lower because of land subsidence on the other hand the tide level become higher and higher because of the climate changing. This make the flood defense standard higher and higher. On general we can clearly see that the land subsidence has caused so dangerous situation in flood defense now in Shanghai.

![Figure 8 high tide level and flood defense criteria](image)
Land subsidence directly reduces the defense and service efficiency of drainage pumping station. Land subsidence made original leveling height lapse. Those involved certain difficulties for tide line analysis, flood prevention plan and management. By the end of 1999, datum level of Wusong Park, Huangpu Park and other hydrographic stations had been amended the values of 3 stations are -0.08m, -0.06m and -0.06m influenced by land subsidence.

Figure 9 shows us another location in Huangpu River. We just study the situation after 1950. From this figure it is clear that because of the subsidence of the ground the flood defense wall have to be built up higher and higher.

![Figure 9 Relation between land subsidence and flood defense](image)

2.4.2 Waterlog and land subsidence

Street waterlog often happens in flood season in city. 292 times of torrential rainwater happened from 1981 to 1994 in streets of Shanghai urban area, while 22 times at the center of the city. The frequency of rain storm almost doubled in the 1990s (3 times per year) compared to the 1980s. Rainstorm often concentrates on the center of the urban area due to the rain island effects. Because of the land subsidence, the flood waters are difficult to be released out of the central area of the city, which might easily cause the water logging disaster. All the rain storms could cause water logging disasters in the past. The drainage system has been improved a lot since 1956 and now it reaches 969 m$^3$/s of the total drain ability, with 161 pump stations and 616 sets of
equipments in the central city. The criteria of rainstorm drainage system is only about once per year (which can discharge 36mm rainstorm per hour in Shanghai). The land subsidence makes the situation even worse. It can not only lead to the damage of drainage system’s equipment but also lead to the drainage system’s criteria lower.

The following figure is about water logging in the street in Shanghai. This happened in 1961. We can see that people use boats as a transportation tool. It was a big storm. So many buildings were flooded because the water can not be pumped out in time.

![Waterlog in the street in Shanghai (1961)](image)

The ground level in lots of the area in the city is less than 3.0~3.5m. In the center of the city the ground level is less than 3.0m. In the mean high tide level situation, water level in rivers is the same to the ground level or higher than the ground level. Most of the river area in Shanghai becomes on-ground River. Some related data can be seen from table 2.
The ground subsidence makes the water level in rivers higher correspondingly which lower the efficiency of the pumping station. This also leads to more damages. The water level in rivers when there is a high tide level is almost the same as the ground level of the city. During this situation the drainage pumping station have to be stopped. For example on August of 2000 there is a high tide level and at the same time there was also a rain storm. The gate which is used to prevent the tide in the port is closed. At that time the water level in the river is 4.1m. It is a dangerous water level. In order not to let the flood defense wall damaged some drainage pumping station had to be stopped working. In 1999 there was still 3 times this kind of situations. There was a storm in the city but the pumps can not be used to drainage water. Then lots of streets were flooded at that time.

### 2.4.3 Tidal disasters and land subsidence

Shanghai is easily to be affected by the tropical cyclone of Pacific Ocean (typhoon). The typhoon appears more often from July to September every year, with an average of more than two times per year. The typhoon attacked the Shanghai city can be divided in three types according to their routes and landfall sites.

Every time, the typhoon is companied with the rainstorm and extreme tidal height. The Huangpu River which runs through the center of Shanghai is a tidal river, with a whole length of dike of 392.5km. The ground elevation is about 3.0 to 4.0 along the Huangpu River, while the high tide level is 3.0 to 4.5m. Due to the land subsidence, the dikes have to be heightened and reinforced again and again. If without the flood wall, the ordinary high tidal level at 3.0 to 4.0m

<table>
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<th>mean tide level</th>
<th>the highest tide level in frequency year</th>
<th>the highest tide level in history</th>
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<tr>
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<td>5.86 0.1 5.54 0.5 5.4 1 5.26 2 2</td>
<td>5.72</td>
</tr>
</tbody>
</table>

Table 2 The tide parameter in Huangpu Park
will lead to the tidal disaster, which might happen up to 400 times a year. Since the year of 1921 8 times tidal calamities happened in the center of thee urban area, and 6 before 1965.

2.4.4 Land subsidence effects on municipal safety

Rate of sedimentation is non-uniform in space which effects on municipal infrastructure become more and more visible. Monitoring manifest that orbital traffic, railway and bridge of Huangpu river are put into running which present uneven sedimentation about one tunnel of orbital traffic, the value is 81.5mm on average, the character of tunnel non-uniform deformation accorded with different rate of sedimentation in space. Land subsidence is a main factor of tunnel sedimentation, but engineering construction near to subway, load on structure and construction effect on soil mass. Those have impact on deformation of tunnel. Soil horizon creeping is a no negligible factor which generated from vehicles vibration.

Figure 11 shows us the subway subsidence and the ground level going down. The line of subway goes down is similar to the ground level going down.

Figure 11: subway's subsidence (L845 is monitoring point of subway tunnel)
3 The analysis on land subsidence

3.1 Reasons of land subsidence

3.1.1 Factors affecting land subsidence

3.1.2.1 The geology factor of the natural power

(1) The internal power: this is including the going down activities of the earth’s crust, earthquake and the activities of volcano etc. If the subsidence is caused by the activities of the earth’s crust, the ground level will go down very slowly. This kind of subsidence normally can not cause hazard result.

(2) The external power: this is including dissolving, oxidization and freeze-resolve etc. If some salt is dissolved, some organic matters are oxidized or some loose sedimentation lose water, the density and the pore’s percentage of the soil will change. This will lead to the land subsidence.

3.1.2.2 the factors of human’s activities

(1) The liquid extracting from the ground: Human’s activities are the important factor for the rapid land subsidence. Among so many human’s activities extracting the liquid under ground is the important factor for the land subsidence. Almost half of subsidence areas in the world are caused by this kind of reason. This kind of subsidence is a gradual evolution period, so normally people can recognize it after the hazard. So the subsidence caused by this kind of reason can lead to the most dangerous situation.

Most of the areas in Shanghai are covered by loose and soft soil. There is plenty of groundwater resource. When the groundwater is extracted out of ground with large scale, some water will release from the pore in the soil. The porosity of the soil will become smaller. The loose soil will deform, so the ground level will become lower which is called as the ground subsidence.
(2) High building factors soils can only be covered by limited burden. If there are more burdens than the limited burden, the soil will deform. This will lead to the subsidence either.

(3) Some vibrant load also can cause ground level going down. For example the subway in cities can lead to land subsidence.

For Shanghai all these kinds of reasons can lead to the land subsidence. But only two reasons are the most important ones. One is the groundwater extracting and another one is the more and more high buildings.

Shanghai locates at the soft soil. In old days people used ground water as the main water resource. Not only all the people drink it but also most of the industries use it as the only water resource. So the ground water use was in a large scale. Ground water decreasing caused deform of soil which makes the ground level goes down. Then land subsidence becomes a big problem.

![Groundwater use time series](figure12.png)

Figure 12 Groundwater use time series (for the whole city of Shanghai)

This figure shows us the amount of ground water abstracting. From the figure we can know from 1960s people had recognized the importance of groundwater extracting. So they limit the amount of groundwater use in the following years.
Another important reason caused the subsidence is the high buildings. More and more high building make the soil covered with more load than it can be loaded. This is also the main reason why there is still so much subsidence after they limit the groundwater extraction in 1990s.

Now land subsidence caused by groundwater is about 70% and caused by high buildings is about 30%.

3.1.2 Heat-island and land subsidence

In summer, the high temperature leads to the peak of water consumption in a year of Shanghai city. Ground water of Shanghai is good in quality, low in temperature, so the extraction of ground water also comes to its peak in summer, which leads to the obvious land subsidence in this season.

Shanghai has obvious heat island phenomenon. Land subsidence area is spatially firmly consistent with heat island district which is normally the economic active zone.

![Figure 13 Head-island in Shanghai](image)

The dark part of the figure is the city center. The heat island happens here.
3.2 The groundwater and the land subsidence

3.2.1 The theory of land subsidence caused by groundwater use

The condensation of the clay is from the change of the load which leads to the effective stress increasing. Then they can get to condensation. According to the theory of the effective stress, in the soil for each point the balance of the press is:

\[ \sigma = \tau + \mu \]

\( \sigma \)------- the total stress

\( \tau \)------- the effective stress on soil particle

\( \mu \) -------the stress loaded on water in the pore

The effective stress’s increasing mainly comes from two ways.

(1) If the total stress \( \sigma \) keeps as a constant but the stress loaded on water in the pore \( \mu \) decreases this can leads to the increase of the effective stress. In this situation the condensation of the soil is from the going down of the groundwater level caused by the pumping or other reasons.

(2) If the stress \( \mu \) loaded on the water in the pore keeps constant and the total stress \( \sigma \) increases this also can lead to the effective stress increasing. This is mainly from the outer load increasing. For example more and more high buildings and shaking or moving load can lead to the load increasing. Some construction action can lead to more attached stress as well.

In old days many authors gave different opinions about the land subsidence. Some of them think that it is the new distortion motion of the earth. Some think that it is the shrinkage and natural compaction of the earth. Others think that it is because of the going up of the sea level. Many researches indicate that the extracting of the groundwater is the outer factor for the land subsidence. The
inner factor is the easy compacted clay and confined aquifer layers. On general land subsidence is caused by high buildings or the extraction of the groundwater, oil or natural gas.

In the confined aquifer when the groundwater is pumped out the groundwater level will go down. According to the theory of the effective stress of the soil the total press caused by the load covered on the soil is undertaken by the water in the pore and the soil structure. That means that the total press is the sum of the press covered on water in the pore and the soil power. If we assume that the total press keeps the same when the groundwater is being pumped, then the press covered on the water decreasing can lead to the increase of the press on the soil particles. This will make the pore volume less than that of before, which means soil shrinks. Figure 14 show how the ground level goes down because of groundwater extraction.

Figure 14 Soil consolidation
Because of the difference of the dank ability of the different soil the change of press in the soil is different. In the sandy layer when the groundwater level goes down this kind of change can happen very fast. But in the clay layer it is very slow for the change of the press. Normally it is several months but sometimes it is maybe twenty years or even more.

Compared to the clay layers the shrinkage of the sandy layer is mainly sliding and recovery or reversible under normal press. For the clay layer it is normally permanent deformity. So in the period of the groundwater going up the recovery mainly comes from the sandy layer.

Figure 15 is the relation between the land subsidence and the groundwater use in Shanghai from 1961 to 2001. This figure shows that on general land subsidence has the same tendency with the groundwater use. The more the groundwater use the more the land subsidence will happen.

This can also be verified by the other cities in the world. Figure 16 shows us the land subsidence and groundwater using in different locations in the world. Location 1 is Osaka of Japan. Location 2 is California State of USA. Location 3 is Tokyo of Japan. Location 4 is Mexico. It also indicates that the more the groundwater is used the more the land subsidence is.
3.2.2 The time series analysis

The following figure is the time series of average land subsidence in Shanghai from 1920 to 2000.

The time in the figure is from 1920 to 2000. We can divide the time in several periods.
1 from 1920 to 1955: In 1921 the land subsidence was first found in Shanghai. From then on the land level went down with an almost steady speed during the following 30 years until 1955. At that time people only just got to know there was this kind of phenomenon in Shanghai. No one put it as an important factor which can affect the city so heavily in the future. So at that time no measures were taken by people. People even did not know why this kind of phenomenon can happen. Also during that period people were busy with the civil war and Second World War. There were not so much money and time which can be used to study this kind hazard. The population did not change so much during this period. So there are not so much changes of the land subsidence every year during this period. That is the reason why it is a leaning line but not a curve from 1920 to 1955.

2 from 1955 to 1963 there is a sharp decrease in the figure. It is because that the ground water use is very much. There are a lot of reasons for this change. At that time the new China was just founded. More and more people came into the city. Then many buildings need to be constructed at that time. So the ground water is a good resource for people to use for building or drinking. So at that time the large amount of ground water was used. Then the ground water level went down so fast that the ground level went down fast either.

3 From 1963 to 1990. The line is almost horizontal. From the figure we can know that the ground level goes down very slowly. At some times the ground level even recoveries. This is mainly because that from 1960s artificial recharge was carried on to prevent the groundwater level going down. Also during this period special rules and laws were published in order to prevent the subsidence of the ground.

4 The forth period is from 1990 to now. People know how important the groundwater level is. So the groundwater level is in control. Yet at this time because of the new policy in China, more and more high buildings come into being. The population becomes larger and larger. So many buildings become the new reason for the ground subsidence. From the figure we can get to know the ground level goes down slowly.
3.3 High buildings and land subsidence

In 1934 the International Restaurant (82 floors) was established which was called the highest building in the Far East. But until the end of the last century the number of the high buildings increases sharply. Now there are more than 100 high buildings which are more than 100 m. There are 3000 buildings which is more than 18 floors. Another 3000 buildings are still being constructed. In the past 15 years there is no other city in the world which has so many high new buildings. In Lujiazui there are so many high skyscrapers. Among them there is the third highest “Jinmao building” on earth and the second highest “Orient Bright Pearl Tower” in the world. This is peerless on earth.

So many high buildings are scenic in Shanghai. But it also brings us lots of problems including land subsidence. During the past ten years that the mushrooming of skyscrapers in central Shanghai has also contributed to the city's creeping subsidence.

So many high buildings give obvious stresses superpose effect between the intensive high-story buildings. This makes the situation even worse. It can be explained clearly by a test model.
Some researchers did a test model about land subsidence caused by high buildings according to the actual situation of Shanghai. This model was done in the laboratory of Tongji University in Shanghai. In the model they use 4 buildings in a modeled area. These 4 buildings are called A, B, C and D. A is built firstly. After A buildings is finished, B building is started to be built. After B building is finished, and then C and D buildings are built at the same time.

The model map is in figure 19:

From the model test the following conclusions can be got:

1) Comparison of the building subsides
Figure 20 Subsidence difference between different buildings

Comparing with the subsiding in the curve (Figure 20) of A, B, C, D four buildings, it can be found that the subsidence of A building is biggest and B building takes second place. The loading of C, D building being exerted finally, it is minimum to subside. It is proved that orders successively of adjoint nearly building of building have obvious influence in subsiding relatively. This is because first built building receive the influence of after built building, the subside quantity produces superposing. The contours of subsiding displayed in the picture have obvious sudden change, making the subsiding amount exceed after built building, also reflect the effect of superposing between the buildings.

2) Comparison of subsidence at the points on the same axis
Points 1, 2, 9, 13, 15 lie the same axis. It can be found through figure 21 that the subsiding of the centre area is biggest, secondly the points of basic width of one time range from the building, then the subsiding of building itself, the minimum one being the point of basic width of 2 times from the building. The regional coverage of the surface subsidence reflected by the high-story buildings should be greater than basic width of 2 times. Because the subsiding value of the point 1 at the border is 30% of building itself, it can not be ignored.

3) Soil pressure change and building subside
Figure 22 shows the relation of subsiding change and soil pressure under the A building. The growth of the soil pressure takes the form of ladder, which shows the superposing effect between the adjoint skyscrapers, and its subsidence demonstrates superposing growth, which proves that influence between intensive high-story buildings is obvious. Stress increase can make individual building subsidence increase, which will exceed their permit subsiding amount and bring the destabilizing factor.

### 3.3.1 The building scope and the land subsidence

During 1990s more and more high buildings came into being in Shanghai because of the new policy of China. Until the end of 1995 there were 1523 high buildings and the total construction area is $2068 \times 10^4 m^2$. Now these kinds of high buildings are increasing at the rate of 120~150 new high buildings every year. So many high buildings in Shanghai lead to more local land subsidence. In these areas the land subsidence is much more than the mean land subsidence in Shanghai.

Here there are four locations which have some data about the building area and land subsidence during different period. Location 1 and location 2 is in the commercial center. Location 3 and location 4 is in the living building center. The red line is the changes of building area while the blue line is the changes of land subsidence.
From the four figures we can know on general the tendency between the two lines is similar. With the area increasing the land subsidence is increasing too. Although the two lines do not match so well, they still can tell us something about general information. From 1970s to 1990s with the building area increasing the land subsidence is increasing either. At the same time the increasing rate of land subsidence has some linear relation with the increasing rate of new building area. In 1980s the new building area is 1~2 times more than that in 1970s. At the same period the land subsidence rate is also increasing 1~2 times. In 1990s the new buildings area is 3~4 times more than that in 1970s and 1 times more than 1980s. At the same time the land subsidence rate is increasing. It is 6~7 times more than that in 1970s and 1~2 times than that in 1980s.

3.3.2 Building space ratio and the land subsidence

The building space ratio means a ratio of the total building area and the land use area in one location. Normally when the ratio is big and the building will be very high. That means more people are living in that building. There are still some relationship between the building space ratio and the land subsidence. We still use the location1, location2, location3 and location4 as an example to analysis this problem.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1</td>
<td>-</td>
<td>0.82</td>
<td>0.96</td>
<td>1.53</td>
</tr>
<tr>
<td>Location 2</td>
<td>-</td>
<td>1.07</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Location 3</td>
<td>-</td>
<td>0.58</td>
<td>0.81</td>
<td>1.18</td>
</tr>
<tr>
<td>Location 4</td>
<td>-</td>
<td>0.44</td>
<td>0.62</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 3 The building space ratio

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1</td>
<td>-</td>
<td>0.3</td>
<td>3.52</td>
<td>12.56</td>
</tr>
<tr>
<td>Location 2</td>
<td>-</td>
<td>2.13</td>
<td>3.16</td>
<td>7.18</td>
</tr>
<tr>
<td>Location 3</td>
<td>-</td>
<td>1.37</td>
<td>4.49</td>
<td>15.14</td>
</tr>
<tr>
<td>Location 4</td>
<td>-</td>
<td>0.98</td>
<td>2.92</td>
<td>7.95</td>
</tr>
</tbody>
</table>

Table 4 The mean land subsidence per year (mm/y)

From the table 3 and table we can know that the building ratio is becoming bigger and bigger. That means the building is becoming higher and higher. So there are more loads on the ground. At the same time the land subsidence is also becoming more and more.

### 3.3.3 The local subsidence and building site preparation

Compared to the subsidence caused by buildings load, the construction operation can lead to local land subsidence either.

The land subsidence caused by the city construction mainly comes from the high building operation such as building site treatment, lowing and drainaging water and sinking peg etc. Building site operation can destroy the balance of the soil around the building site if there are some sand layers saturated with water or mud soft layer destroyed. Sometimes sand can be pumped out together with water when lowing groundwater level in order to make a building site. So this will lead to the land subsidence around the building site. When digging some channel underground there will be more land subsidence. Before digging the channel underground, the groundwater level should be lowered down in order to work well. This is the same theory with pumping groundwater.
During the operation of lowering groundwater table in building site operation the settlement of ground can be explained in table 5:

<table>
<thead>
<tr>
<th>Name of area</th>
<th>Affected area (from the building site)</th>
<th>Subsidence</th>
<th>Mean hydraulic gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Largely affected area</td>
<td>(0~3)S_w</td>
<td>(0~0,73)ΔS</td>
<td>0,09</td>
</tr>
<tr>
<td>Lightly affected area</td>
<td>(3~10)S_w</td>
<td>(0,73~0,45)ΔS</td>
<td>0,04</td>
</tr>
<tr>
<td>Little affected area</td>
<td>(10~30)S_w</td>
<td>(0,45~0,12)ΔS</td>
<td>0,0165</td>
</tr>
</tbody>
</table>

Table 5 Ground settlement caused by groundwater table variation

In the table 5 S_w means the change of water level. ΔS means the total ground subsidence. In this test the building site area is 200 m², the change of water level is 10m.

The settlement period is showed in table 6:

<table>
<thead>
<tr>
<th>Name of period</th>
<th>Time (d)</th>
<th>Percentage of total ground subsidence (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling period</td>
<td>20~35</td>
<td>0,6~70</td>
</tr>
<tr>
<td>Lasting period</td>
<td>30~50</td>
<td>0,25~30</td>
</tr>
<tr>
<td>Stable period</td>
<td>150~200</td>
<td>0,05~10</td>
</tr>
</tbody>
</table>

Table 6 Ground settlement period

Compared to the land subsidence caused by loads, the building site operation (site lowering groundwater) can lead to ground sinking fast. Now in the center of Shanghai, it is one of the important reasons which contribute to land subsidence after 1990.

The theory is when groundwater is pumping out of the ground, the groundwater level variation can lead to the change of the ground level. The local land subsidence consists of two parts: (1) the condensation deformation of the aquifer: The intensity of the sand in aquifer is high and at the same time there is water with pressure around the particle. When the water level changes not so much, the position between sand particles can not adjust. On the whole the degree of condensation is not so much and it can become steady very fast. (2) The condensation of the upper clay layer: When pumping groundwater in upper clay layer water can release out and the clay can appear condensation.
When groundwater is being pumped out of the ground, the pressure on the water in the pore can decrease because of drainage. If the water level decreases with $\Delta H$, the pore pressure will decrease with $\gamma_w \cdot \Delta H$. The total pressure $\sigma$ keeps the same. According to the effective stress theory $\sigma = \tau + \mu$, more pressure will be on the soil particles. So this makes the aquifer more condensation. With the time going on of pumping groundwater, the condensation of the confined aquifer becomes stable gradually. After this the upper clay layer begins to release water and condensation will happen. The infiltration coefficient and the condensation coefficient is very low. The condensation can happen very slowly. Even the groundwater level can go back the original level, this kind of phenomenon will still continue for some time and then stop. So the local land subsidence because of pumping groundwater during building site operation can happen not only in the confined aquifer but also in the clay layers.

### 3.4 The current characters of land subsidence in Shanghai

#### 3.4.1 Recent land subsidence character

There are mainly clay and sandy soil in Shanghai. According to the land subsidence and character of the soil we can divide the soil between 0 m to 300 m underground into 3 layers.

Shallow soil layer: this is about the soil between 0m to 40m underground. This mainly is including the first and second pressed layer and the first confined aquifer. The first and second pressed layers mainly consist of muddy clay and sandy clay. They have the character of much pore, low intensity, and easy deform. The operation of building base and road base can lead to the local subsidence.

Middle and upper layer: they are between 40 to 150m underground. They consist of the third pressed layer and the II and III confined aquifers.
The deeper layer: the depth is about 150m to 300m underground. They mainly consist of the IV and V confined aquifer layers. These two aquifers are the main aquifers which are used to pump groundwater now.

<table>
<thead>
<tr>
<th>soil layer</th>
<th>accumulative subsidence(mm)</th>
<th>the mean value(mm/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>shallow layer</td>
<td>45</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.9</td>
</tr>
<tr>
<td>middle and upper layer</td>
<td>5</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.3</td>
</tr>
<tr>
<td>deep layer</td>
<td>20.22</td>
<td>37.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 7 Soil layer land subsidence analysis

From the table we can draw a conclusion that land subsidence now in Shanghai is mainly from the deep layer.

3.4.2 The analysis of each confined aquifer

If we analysis the characteristic of each aquifer, we can easily understand the situation now in detail. On general since 1966 some measures have been used to control the land subsidence. To 1989 there were only 3.4mm/y land subsidence happening. But after 1990 more groundwater was pumped out of the ground and at the same time some construction activities give more and more affection to the land subsidence. The rate of land subsidence in Shanghai after 1990 becomes fast. The groundwater extraction is also the important reason for the ground level change. But with the change of aquifers used to extract the groundwater, the state of every aquifer and the proportion which is the percentage of the total land subsidence for each layer varies a lot. (Table 8)
<table>
<thead>
<tr>
<th>soil layer</th>
<th>mean thickness (m)</th>
<th>deformation rate (mm/y)</th>
<th>accumulative subsidence (mm)</th>
<th>Contribution rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>the 1st soft soil layer</td>
<td>16</td>
<td>1.24</td>
<td>18.65</td>
<td>18.90</td>
</tr>
<tr>
<td>the 2nd soft soil layer</td>
<td>15</td>
<td>0.72</td>
<td>10.86</td>
<td>11.00</td>
</tr>
<tr>
<td>the 1st confined aquifer</td>
<td>23</td>
<td>0.41</td>
<td>6.20</td>
<td>6.30</td>
</tr>
<tr>
<td>the 3rd soft soil layer</td>
<td>30</td>
<td>1.23</td>
<td>18.47</td>
<td>18.70</td>
</tr>
<tr>
<td>the 2nd confined aquifer</td>
<td>34</td>
<td>0.18</td>
<td>2.67</td>
<td>2.70</td>
</tr>
<tr>
<td>the 3rd confined aquifer</td>
<td>40</td>
<td>0.32</td>
<td>4.82</td>
<td>4.90</td>
</tr>
<tr>
<td>the 4th confined aquifer</td>
<td>87</td>
<td>3.13</td>
<td>31.90</td>
<td>32.30</td>
</tr>
<tr>
<td>the 5th confined aquifer</td>
<td>78</td>
<td>0.36</td>
<td>5.33</td>
<td>5.40</td>
</tr>
<tr>
<td>sum</td>
<td>323</td>
<td>7.59</td>
<td>98.9</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Table 8** Detail analysis about land subsidence in Shanghai downtown

Note: the contribution rate is the percentage of different soil layers’ subsidence in a certain period.
The table indicates that in the shallow soil layers the contribution rate become lower but the deformation rate become higher than before. The main reason is that so many new buildings give more loads to the ground and that during building site preparation groundwater level was lowed this disordered the structure of the soil.

(1) the 2th and 3th confined aquifers:

These two aquifers are the main layers for groundwater extraction before 1963. Groundwater extraction with large scale leads to the filler of groundwater level in Shanghai downtown. At the center of the filler the groundwater level is even 35 m lower than that of other place. In 1963 the groundwater extraction was limited. In 1966 the groundwater level went up again after the artificial recharge. To the winter of 1968 the reversed filler came into being. The 2th and 3th aquifers are the main layers that are used for artificial recharge. There is a period change of groundwater level with the affection of seasonal groundwater extraction and artificial recharge. That means on summer more groundwater is used than on winter the groundwater level become a filler shape while artificial recharge is mainly on winter so the reverse filler came out. There was little recover of the soil in 1965. In 1966 the recover became more with the going up of the groundwater level. There were 3.21 to 17.83 mm recover of the 2th and the 3th confined aquifers from 1966 to 1972.

![Figure 24 The 2th confined aquifer groundwater level variation](image-url)
After 1972 with the groundwater extraction and artificial recharge going on, the groundwater level appears period change and at the same time it goes down slowly. But after 1990 because of the decrease of the artificial recharge, the groundwater level goes down faster than before in the 2th and 3th aquifers. In the 3rd confined aquifer layers, the contribution rate increases from 4.87% in 1995 to 12.40% in 2000.

(2) the 4th confined aquifer

Before 1968 with the groundwater level going up, there is little recovery in the 4th confined aquifer. For example, the recovery of the ground level is about 4.43mm and 9.19mm in Labour Park and Beixinjing respectively. After 1968 groundwater extraction was moved from the 2th and 3th aquifers to the 4th and
the 5th aquifers. The groundwater level goes down gradually. To 1980 the low water level kept between -15m to -26m. At the beginning of 1990s with the groundwater level going down the deformation rate increased gradually every year. In the period of high groundwater level the recovery of aquifer layer becomes less. At the period of low groundwater level the degree of condensation increased. With the groundwater level going down this layer represents condensation status for the whole year. The subsidence each year is between 12mm/y to 45mm/y. This makes the contribution rate of the 4th aquifer to the total land subsidence increases to 49.27%. In 1998 the government limited the groundwater extraction in this aquifer. The groundwater level went up again but not so much. The deformation rate became less. But the 4th and 5th aquifer still appear condensation status for the whole year.

(3) The 5th confined aquifer

Because it is only in the area of north part of Shanghai downtown, there are not so many records about groundwater level change and some related information. But from some of the data we can know that it appears the similar character to the 4th aquifer. Because there is not so much groundwater in the 5th aquifer as that in 4th aquifer, the intensity of the groundwater extraction in this aquifer is less than that in the 4th aquifer. But the groundwater level changes more than that of the 4th aquifer.
4 The prediction of land subsidence in Shanghai

4.1 The analysis of groundwater requirement

The main reason of land subsidence in Shanghai is the groundwater using. Water resource plays very important role in the development of economic. In the further development of Shanghai economic the requirement of water resource will be more than the past. According to some rules of the administration some old water supply plant will be improved and some new water supply treatment plant will be built. The new water supply project from the Yangtze River is going on now. The integrated treatment to the water in Huangpu River goes on well. These can indicate us that in the economic development in future the requirement for the water resource mainly depends on the surface water source. With the development of the technology the industry will mainly depend on the technology but not the labor. In the past the spin industry need lots of water. Now new technology is used, which leads to the decrease of the water resource. With the new policy and treatment technology improvement more and more surface water can be used by more industries. This change the bad situation (in the past the groundwater was mainly used for industry while the surface used for the drinking water).

This kind of change can not be done very soon. The water quality in the Huangpu River can not be improved within one or two years. The new water supply can not satisfy all the people now. Some cooling industry needs groundwater. Groundwater price is lower than the treated surface water. More measures are still needed if we want that different quality of water can be supplied to different users. In the following years the water still can not meet all the users. So the groundwater using by more user which is not reasonable can not be avoided. The groundwater using will still be with a large scale.
4.2 The deform analysis of the soil

There are two kinds of soils generally in Shanghai. One is the sandy soil and another is the clay. For the sandy soil aquifer the deformation can rebound with some scale. The sandy grain can support the structure. So the change of the soil can not be the worst situation with the change of water table. For the clay soil in the deeper layer, they are dehydration. The degree of concretion is high and the structure is tightness and hard. It can not be compress with large scale. But for the clay layer which is in the layer between 0 and 75m underground, the soil contains much water and the porosity is high. The natural concretion has not finished. This is especially obvious for the shallow layer from 0 to 40m underground. There is not so much change with the artificial recharge. They are always in the status of being pressed. So the shallow clay layer will be very important in the land subsidence of Shanghai in the future.

The water flow in the soft clay layer is viscous. Water in the soil can not be drained very fast. At the same time the stress on this kind of soil is not so much in the history. So it can deform with load. In future the land subsidence will increase. With the degree of concretion increasing the land subsidence will become slow.

4.3 The city construction

With the city developing all the buildings and construction operation will give more effect on the land subsidence in Shanghai. The effect caused by buildings is local but on the long view the load will be there for long time. More and more buildings can give the general bad effect on ground subsidence, because ground sinking caused by high building is not immediate. According to some project’s practice when buildings are finished after 5 or 10 years the soil condensation can finish only 75%~95%. In the coming years the population in Shanghai will be more than 20 millions. More people need more buildings. Then in the coming future more and more buildings will be built in
Shanghai. This will give more loads on the ground. So the land subsidence caused by buildings will have more percentage.
5 The current methods evaluation and suggestions for the future

In China Shanghai is the earliest city to use effective methods to control its land subsidence in China from the beginning of the 1960s. The ways used by this city include injection of water through wells to recharge the principal aquifers, reduction of pumping draft groundwater, promulgating the regulation of groundwater use etc. Now effective result has been gotten. Before taking measures to control the land subsidence (1921-1964) the annual mean land subsidence is about 38mm/y, after taking measures (1965-2000) the annual mean land subsidence decreased to 6mm/y. especially from 1965 to 1990 the mean land subsidence is less than 5mm/y. In 1990s because of high density of buildings the mean value is more than 10mm/y. From the data we can know that the measures taken by the government take effect.

5.1 The current methods and measures

The measures taken by Shanghai are mainly including engineering measures some policy measures. In detail there are artificial recharge, groundwater use plan, adjust the aquifer of groundwater extraction, making the scheme of annual groundwater pumping, the ground subsidence monitoring and so on.

(1) The groundwater artificial recharge

Repressuring of confined aquifer systems by artificial recharge directly through wells, although expensive, may prove to be the only practical way to slow down the land subsidence. The injection of river water through production wells is undertaken chiefly in the winter months when many factories are not operating and when the river water is coldest. Because much of the groundwater withdrawn is used for cooling purposes in the factories in the summer, any decrease in water temperature in the aquifers is beneficial. From the winter of 1965 to 2000 the total recharged water to ground is about 200 million $m^3$. 
This figure shows us the change of the artificial recharge. The amount of groundwater artificial recharge is made according to the land subsidence plan and groundwater use plan.

The effect of the groundwater artificial recharge is notable. In 1966 at the center of the city the ground rebounded which is about 6.3mm. From 1967 to 1990 more water was injected into the ground. The annual mean land subsidence is about 0~5mm. After 1990 in urban area of Shanghai the recharged water kept almost the same but at suburb more groundwater was used with large scale. Then the groundwater level had the trend of going down, which lead to the land subsidence more than before. But at the center of the city the amount of water recharged is still more than the amount of water pumped out from the ground. So there is not so much land subsidence as the period before 1960. Artificial recharge can slower the land subsidence.

(2) Ground water use plan

Liming groundwater using is on the condition of guaranteeing the industry going well to use surface water instead of groundwater as water resource. Using artificial cooling facilities substitute groundwater as cooling water resource. From 1964 groundwater was first limited to use. In 1963 it is about 110 million m$^3$ but during 1966 to 1972 it is only 11 million m$^3$. Some investigation can indicate that the groundwater level goes up again with the
decrease of groundwater extraction. The land subsidence becomes less at the same time and even can recovery. Great effect had been gotten by limiting the groundwater extraction. Figure 24 shows how the government controls the land subsidence in Shanghai. The allowed volume of groundwater use is made according to the land subsidence plan. They want to control the land subsidence within 10mm/y. In 2005 the actual subsidence rate is 8.7mm/y. In 2010 the rate will be within 5mm/y. The planed volume means that Shanghai Water Board makes this target according to the factory or some industry's groundwater requirement. The pumped volume is the actual groundwater pumped from the ground. The amount of groundwater extraction is planed to decrease from 74.5 million m$^3$/y in 2005 to less than 25 million m$^3$/y in 2010. Figure 25 shows that the planed target of land subsidence and the actual value. From the result conclusion can be got that the government of Shanghai have a good plan and succeed in the land subsidence control.

![Figure 28](image-url)
(3) The aquifer change of groundwater extraction

Before 1966 groundwater was pumped out mainly from the first aquifer and the second aquifer. For example in 1965 in the total groundwater pumped out from the ground there are 71.3% of them which was pumped out from the first and the second aquifer. Some experiments show that the shallow soil layer within 75m underground is compressed easily because the extraction from the first and the second layers. Yet if the same amount of groundwater is pumped out from the fourth and the fifth aquifers there will be less land subsidence. As a result from 1972 to now the 4th and the 5th aquifers become the main layers which are used to pump out the groundwater. From 1980 to 1995 the groundwater the groundwater pumped out from the 4th and 5th is about 73.2% of total groundwater pumped out from the ground. Good effects have been achieved by adjusting the aquifer layers of groundwater extraction. In fact the land subsidence decreased 5mm on average every year because of the aquifers changing of groundwater use.

(4) Making the scheme of groundwater use and artificial recharge every year

The annual groundwater use and recharge scheme was first made in 1966. This scheme leads to the dynamic balance between the groundwater use and artificial recharge. Because of this largest amount of groundwater can be got with least land subsidence. Before 1965 there was no integrated plan and management about groundwater. The largest amount of groundwater pumped
from the ground for one year is more than $200\text{ million m}^3$. They are mainly from the second and the third aquifers which made the mean accumulative subsidence about $1.69\text{ m}$ in the city center. In somewhere it is about $2.63\text{ m}$. The most rapid subsidence is $110\text{ mm/y}$. After 1966 there is groundwater use scheme every year. With these schemes and plans during the 30 years (1966-1995) in the city center the accumulative land subsidence is only $115.6\text{ mm}$. This number is the same as the annual mean largest subsidence before 1965 and it is only $6.6\%$ of the total subsidence of former 45 years.

(5) The research and monitoring of land subsidence tendency

In 1962 land subsidence monitoring was first done with a large scale in Shanghai which is the earliest city who made research and monitoring in China. Now in the Shanghai there is a general net of land subsidence monitoring. Big harvest has been got from these studies and monitoring. This kind of research and monitoring is the basic work in order to prevent the land subsidence. The results got from the research and the monitoring play very important role in controlling the land subsidence of Shanghai.

(6) The legal measures to prevent land subsidence

In 1963 some laws were first used to prevent the land subsidence in Shanghai. On June of 1963 “the deep well management methods of Shanghai” was first published by the people’s committee meeting of Shanghai which said: “the groundwater resource should be used and protected properly. The land subsidence should be prevented and groundwater use should be limited.” What’s more some related administrative laws were published as well. For example on August 21th of 1996 “the administrative methods used to monitor the land subsidence in Shanghai” came out. From table 7 the two periods can be easily understood well. First from 1921 to 1965 there was no measures used to control land subsidence. Land subsidence increased gradually. Especially during 1957~1967 the annual settling volume was $287\text{ mm/y}$ (now it is within $10\text{ mm/y}$). Some measures were taken after 1966. We got better result. From 1966 to 1971 there were $17\text{ mm/y}$ rebound of ground level. After that the
annual settling volume is smaller than before. To 2010 the land subsidence will be planned to control within 5mm/year.

5.2 The current questions

5.2.1 The whole area study

Land subsidence a primary geology disaster in Shanghai. Lots of measures have been taken to control this problem. Now in Shanghai good monitoring net work has been established. But the land subsidence is happening not only in Shanghai the whole Yangtze Delta area land subsidence is happening as well. The situation is not so worse but we still can not neglect it. Now in the Yangtze Delta area the area of land subsidence which is more than 200mm is almost 10 thousand km$^2$ and which is more than 1.0m is about 340 km$^2$. The land subsidence area which is between 0.6 to 1.0m is about 1350 km$^2$. In the Yangtze Delta area the groundwater is a whole net system. If we only control the groundwater using in Shanghai, land subsidence can still happen. If we pump the groundwater around Shanghai, the groundwater level will become lower. Then the groundwater will flow from the ground under Shanghai to the outside. Then the groundwater level will goes down as well. So the land subsidence can happen. Now the government has known the theory. But there are still some other problems:

(1) There is no the whole net monitoring system. The whole change law can not be known. Until to now there is no water environment net monitoring system and land subsidence net monitoring system. There are local monitoring stations in each city. There is seldom net monitoring system which can monitor the whole area groundwater system. There are sedimentation marks, ground bench marks and GPS system in Shanghai. In Changzhou of Jiangsu province and Ningbo of Zhejiang province there is a set of sedimentation marks. But for the other place in Yangtze Delta river there is not this kind of monitoring system.

(2) There is seldom information for sharing in the whole area. The pole of monitoring data can not play well. Until to now only the minority of the
groundwater monitoring data can be shared, and the majority of the data can still be used separately. Some good research results and experience can not be communicated well.

(3) There is no the whole area management. Maybe in Shanghai the land subsidence can be controlled but in other part of Yangtze River the land subsidence can become serious. For the whole area cure only the local government or department can not finish it separately. Now the cities in Yangtze Delta area only control the land subsidence separately. There is seldom the whole area management method.

5.2.2 Aquifer lays research

Now the main research is mainly focus on the shallow soil layers. There are not so many researches about the deeper soil layers. From 1991 to 1996 the subsidence caused by the deeper soil layers is about 45.2% of the total. So it is necessary to do some study on the deeper soil layers. If we know the theory of the subsidence for deep soil layers, we can better improve the accuracy of calculation.

The aquifer IV and aquifer V has plenty of ground water. More and more ground water is pumped out of the ground from these two layers. From 1991~1996 the groundwater pumped out from the ground are about 107 million m$^3$ totally. However from 1966 to 1990 there is only 64 million m$^3$ groundwater extracted from these two aquifers. The ground water level in the layer aquifer IV and aquifer V goes down at the rate of 1.5m/y and 2.5m/y respectively. So this means that the recharge of groundwater to these two layers is not enough and that the groundwater pumped out from these two layers mainly comes from the storage resource. There are clay layers in the aquifer IV and aquifer V, so if we continue to pump water from these two aquifer layers, the groundwater level will continue to go down. Then the subsidence caused by it will become more and more. But now there is not so much research on the deeper aquifer layers. The theory should be different between the upper aquifer layer and deeper layer. So it is very necessary to do some research on the deeper aquifers layers.
5.2.3 Groundwater equilibration

According to the groundwater exploration plan, in 2010 the groundwater extraction and the artificial recharge will be the same which is 25 million m$^3$/y. So an equilibration to the groundwater in Shanghai can be got. Some people think that this is the best result for land subsidence prevention, because that means the groundwater level does not change and there will be no land subsidence happen caused by groundwater change.

However even no one uses groundwater in Shanghai in 2010 the land will still go down within 5mm/y according to the plan. One reason is that high density of buildings can lead to land subsidence. Another reason is that the soil underground can consolidate very slowly. Maybe the groundwater we use can cause land subsidence after 10 or 20 years.

Now the question comes out. If we do not care about the factors in the last paragraph and an equilibration is got at the same time, does that mean the ground level will not go down?

The answer can not be answered only with one word “yes” or “no”. As we know in the groundwater net system there is a dynamic balance between natural recharge and discharge. Groundwater in Shanghai is only one part of the groundwater system in Yangtze Delta area. According to some research the natural recharge location for this groundwater net is in Jiangsu Province and Zhejiang Province. Now in these two provinces groundwater use is also over exploration which leads to land subsidence either. The government in Shanghai only manages land subsidence and makes laws in Shanghai. Jiangsu province manages groundwater by itself. They do not administrate as a whole. Groundwater level’s change in Jiangsu province can also lead to the change of groundwater in Shanghai. What we called “equilibration of groundwater in Shanghai” is not real equilibration. It is only a local equilibration. When people are making a plan of land subsidence this question should be considerate.
How much groundwater will flow to the ground of Shanghai and how much groundwater can be used in the future is still a big project for people to study in order to make the best plan of groundwater extraction plan and land subsidence prevention plan.

### 5.2.4 Government management and organization

#### 1 water management system in China

The following is the structure of Chinese water management government. The highest authority of water management in China is water ministerial department of PRC in Beijing. Shanghai Water Board is the second level administration department. In 2000 and 2001 Shanghai Water Board had a reform. New Shanghai Water board was established. Now I will tell the difference between the new Shanghai Water Board and the old Shanghai Water board and some existing questions.

The old Shanghai Water Board was founded after the new China was established in 1950s. It only charged water resource and water quantity. At that time the City Construction Bureau managed the groundwater in urban area and water supply and drainage system. While the groundwater in rural area was administrated by the Geology Bureau. The water quality is under the charge of the Environmental Protective Bureau. So many departments lead to lots of difficulties during the period of water use. For example when the government wants to control the land subsidence, the groundwater control is very important. The integrated management of groundwater is necessary because the groundwater is a whole system underground. But at that time groundwater in urban area and rural area was charged with different departments. It is difficult to make the plan of groundwater use and artificial recharge according to the whole system of groundwater. So reform is very necessary for all the old Water Board System. Now only some big cities like Shanghai reformed the old system. Water Board in most of the provinces are still in the old system. They are going to found a new Water Board like that of Shanghai.
After the reform now the new Shanghai water board is charging of all the business related to water. This makes it easy to give the water integrated management. The new Shanghai Water Board is still in the period of exploration. She has more authorities than before as well as the responsibility. For instance urban water management system was administrated by the Construction Bureau before 2000 but now by the new Shanghai Water Board. How to solve the problems of conflicts between the water supply facilities and gas or other city facilities is a new challenge for them. For the water price determination the new Shanghai Water Board should make more cooperation...
with the Worth Bureau. New Shanghai Water Board give new hope and the new more challenges at the same time.

2 The land subsidence management system of Shanghai

![Diagram of the land subsidence management system in Shanghai](image)

The Land Subsidence Administration Office of Shanghai belongs to Municipal Housing, Land and Resource Administration Bureau. It charges the monitoring and supervises of the land subsidence. Shanghai Water Board is in charge of the groundwater. According to the information from different departments the City Planning Bureau give the plan how to control the ground sinking and groundwater level. Then Shanghai Water Board will take some measures to limit the groundwater use. Land Subsidence Administration Office will monitor the land subsidence and make some analysis according to the information from the Shanghai Water Board. Every year they give reports to the City Plan Bureau in order that they can make conclusion and new plan.
5.3 Suggestions on next step

5.3.1 Ground water utilization study

Groundwater overexploitation is the leading reason of land subsidence in Shanghai. Groundwater utilization should be given a good plan in order to prevent land subsidence. What is a good plan? Now the government is trying to decrease the amount of groundwater extraction as less as possible. To 2010 the groundwater extraction will equal to the artificial recharge in Shanghai. After that what should they do? There are some arguments:

a. Keep the equilibration between groundwater extraction and artificial recharge.
b. Going on increasing the artificial recharge and decreasing the groundwater utilization until no groundwater is extracted from the ground.
c. Find a suitable amount of groundwater that can be used every year.

Each scheme has their “enough” reasons to support itself. People holding the opinion ‘a’ think that China is a developing country. For Shanghai it is still a developing city. Water supply system can not cover all the areas in Shanghai especially in rural areas. Using surface water instead of groundwater is not practical. There are still some industries which depend on groundwater so much. We can not change the situation so fast in the short period. If the equilibration can be got that is enough for land subsidence in the special situation.

People who hold the view of scheme ‘b’ think that groundwater is the leading factor that leads to land subsidence. No groundwater used is the best result for us to control the land subsidence. They think that maybe now what we cost is more, but compared to the lost in the future caused by land subsidence, it is worth. They think people should give more invest on this subject.

People holding the opinion ‘c’ thinks that groundwater resource is a dynamic balanced system. If we can use it with a suitable scale which can not lead to land subsidence happening because there are some natural recharging areas.
On one hand we can use this cheap groundwater resource on the other hand we can avoid land subsidence.

But for these three schemes there is no enough actual data supporting. Some models should be done in order to find the suitable solution. In the model every thing should be including in. it is not a simple problem between land subsidence and groundwater use. There is other factors which should be included in such as economic and population etc. It is complex system engineering. So the next step of research should give more attention on this direction.

5.3.2 Integrated management for the Yangtze Delta

From the analysis we can know that if we want to cure the land subsidence problem in Shanghai thoroughly we must do well the integrated management of the Yangtze Delta area.

(1) A good layout about the land subsidence prevention is needed for the whole Yangtze Delta area management. Whole area land subsidence prevention is system engineering. A scientific and feasible prevention layout is needed. This layout is including: the investigation evaluation of groundwater, the monitoring net, groundwater mining, artificial recharge, using water economically, looking for the fungible water resource and the integrated prevention between city and the suburb and different cities etc. A good layout should match the productivity development level. The integrated management is necessary for the whole area. The relation between the groundwater pumping, artificial recharge and using water economically must be done well. Anyway the government should learn more from the experience and make a feasible land subsidence prevention layout.

(2) The monitoring net should be established for the Yangtze Delta area. The municipal government of Shanghai has invested 3.5 million Euros to establish the new land subsidence monitoring net. Now according to the requirement of economic development for the Yangtze Delta area the National Geology Investigation Bureau give a design on how to manage the land subsidence in
Yangtze Delta area. In the design there are 102 first class GPS monitoring spots and 740 second class GPS monitoring spots. Together with the leveling I and II, in the area of 30 thousand m² area the land subsidence can be monitored. We should establish the local monitoring net based on the whole net system. Then the monitoring data can be collected automatically, transferred in time and analysis automatically. At the same time some investigation should be done about the relation between the land subsidence and city plan, flood defense, city establishment and ground space using. We should study the land subsidence in detail and get the conclusion of the prevention policy, technology method and criteria.

(3) More cooperation between different area and cities is needed. Periodic meeting should be hold to discuss the problems and experience for the whole Yangtze Delta area. Each city should help each other. The land subsidence prevention work should be done properly under the cooperation.

(4) Advanced technology should be used to prevent the land subsidence. In the world there are lots of areas which have the land subsidence problems. They have their own experience and technology. We should learn from them. The high technology can make the data more reliable. We can establish the dynamic management system using the modern information technology.

5.3.3 Water use in an efficient and suitable way

Groundwater over exploration is the leading reason for land subsidence in Shanghai. An efficient and suitable way to use water resource would be helpful for us to solve the problem of land subsidence.

(1) Encouraging the activity of economically using water:

In order to improve the situation economically using water should be encouraged. Now the activity of wasting water is still very critical. Some of people waste lots of water every day. This should be limited by increase water price. In rural areas the efficient irrigation is needed. On the other hand waste water reuse should also be encouraged. Some waste water can be reused by
simple treatment. Some simple tools can be used to storage the rain water on the top of building. This kind of water can be used to flush the stinkpot. New technology should be used to make some good tools to reuse the water. For example if there are some simple tools which can treat the water which is used to clean the vegetable and hand, this kind of water can be become ‘clean’ again. It can be used to clean the floor or flush the stinkpot.

(2) Providing more advertise. The idea of using water in an efficient way should be known by everyone. The government should make everyone realize how important it is to economically use groundwater. People should know more about the theory of land subsidence and put in heart the harm of land subsidence.

Now some people only know there is land subsidence happening but they do not know how important it is for the sustainable development of Shanghai. They do not know what they can do and what they should do. Even some people think it is not their case to think so many things. So they waste water and pump water without permitting. This kind of work should be done from the children when they are at school.

(3) Using more surface instead of groundwater

Land subsidence is a big problem now because of the groundwater extraction. People recognize the dangerous situation. The government has taken lots of measures to control the land subsidence. One method is to change the groundwater pumped location. From 1970s the government adjusted the aquifer layers which were used to pump groundwater. This method played good roles and slowed down the land subsidence. But it just can slow down the land subsidence and it can not prevent the land subsidence. From table 6 we can know that there are almost 50% land subsidence which is caused by the deformation of the 4th confined aquifer. This means that adjusting the aquifer layers can only be viewed as a transition measure when water resource is not enough.

Another way is to limit the groundwater using. Yet the population in Shanghai is becoming larger and larger. So water demand will increase as well. But the
groundwater can not be used so much any more. If we can use more surface water as water resource to supply Shanghai, we can solve this problem properly. But now the water quality of surface water is not good enough to use. Lots of treatment plants are needed if using surface water as the main water resource. The city has more than 30 mineral-water producers. They consume about 600,000 cubic meters of underground water a year but are responsible for a very tiny percentage of the city's total subsidence. Water supply system can not cover all the areas in Shanghai especially in rural areas. For financial reasons this solution can only be got step by step. At the same time some related laws should be made or improve efficiency of old plants to protect the surface water quality. If the surface water quality keeps well, less treatment should be done before it is used. So if we use surface water as main water supply resource, we must one hand control the pollution source and on the other hand improve the efficiency of treatment plants.

(4) Organization and law

Shanghai is the first city which uses the administrative code to control the land subsidence in China. In 1963 in order to control the land subsidence and limit pumping the groundwater the government enforced the regulation “The management law about the deep well in Shanghai”. This law gave some limit about the permit of cutting new well, the amount of pumping groundwater, and groundwater fees. To some deep well which is easy to artificial recharge some hortative measures is given to encourage the people to give more help to the artificial recharge. This law was renewed in 1979, 1982 and 1997. In 1996 in order to protect the monitoring equipment of land subsidence the government blow the new law” The management law about land subsidence monitoring equipment in Shanghai”.

Now some rules are published by Shanghai Water Board. Anyone who wants to use groundwater must apply for the groundwater use license. If someone makes a well to pump groundwater without the license he will be fined from 1 thousand Euros to 3 thousand Euros. If he uses groundwater more than the permitted value he will be fined with the price 10 times more than the normal groundwater price.
All these rules play very important role during the period of groundwater control. But only knowing these rules are not enough. Related organization should strengthen the enforcing of law. In some place people know the importance of land subsidence. They also know the main reason is groundwater using. But they still steal the groundwater with large scale. For this kind of action only economical punishment is not enough. If there is related law to some worst situation the guilty people should be put into prison.

The existing law about the land subsidence and groundwater control should be improved. In some cases the existing law can not guide all the behavior that is not good to the land subsidence. So the law should be completed step by step.

### 5.3.4 Sustainable development

Sustainable development is accepted by more and more people. It means on one hand we make progress and development, on the other hand what we do and what we use now can not lead to the damage which can affect future’s development. In another word it means what we do can not give bad effect to our sons or grandsons. The emphasis of sustainable development is “development of society” and “protection of resource”

The view of sustainable development is suitable for land subsidence prevention. People in the past thought that the groundwater was cheap and unlimited natural resource. They use groundwater as much as possible. Now we get punishment from what they did. We should not do in the same way.
In order to get the sustainable development figure 33 gives the clear sketch of land subsidence prevention. In the left side our purpose is to get good environment, at least damage, enough water resource and society development. In order to get the purpose we must take some measures such as laws use and administration, some engineering measures, policy and technical measures. But the emphasis is environment protection. The priorities are environment, society and economic (figure 34). So when the government make general plan on the city. They should firstly put environment as the position.
5.3.5 A complex system engineering

Land subsidence prevention is complex system engineering. It is related to society development, economic level, geology and population etc. The world and earth are changing all the time. We must on one side study on the change of the nature on the other side we take consideration of every kinds of human being’s effects. For big cities, we should first know the geology information and then research on the exploiting of water resource, spatial planning, Environmental conservation, flood defense and so on (figure 35). Disaster prevention and cure involve integrated study: groundwater resource management, society, economy law and so on.

![Diagram of land subsidence management](image)

Figure 35 Other factors on management of land subsidence

In order to get good result form land subsidence prevention all the information should be taken into consideration to make a good plan. Our purpose of land subsidence prevention is to make the lowest social risk and cost. The behavior of us should not give bad effects on future’s development.

In this procession, not only the technical means can be referred, but also some social and economic problem. Those are must head out on the premise of law, administrative measure and economic security, powerful supposed by government. Efforts on prevention and cure will be come into fruition. All these factors can be included in the sketch.
The instructive idea about land subsidence management is the following. The purpose is to serve the macroeconomics and development layout and improve the quality of people’s life standard and circumstance. Depending on the development of technology and using new thought, new theory, new method to do well the integrated investigate and evaluation about the geology resource and environment. We should improve the standard of protection about the geology and reasonable exploit. The predictive warning system and effective monitoring system should be used more on the calamity. The urgent measure and related organization system should be organized well.

Land subsidence in Shanghai is a latent calamity. So the fundamental principle should be monitoring and anticipating. For the existing calamity we should take effective measure to prevent its development and decrease the bad effect.

On the other hand land subsidence can be seen as the result of the development unbalance of human being, resource and environment. This result leads to the calamity of human being. So the city plan and construction should take consideration on the bad effect. Some related law should embody this kind of idea.
6 Conclusions

The first part of this report tries to give people a better understanding of land subsidence in Shanghai. Shanghai, as the largest industrial and most developed city in China, is facing the problem of land subsidence. Since 1921 ground has sunk almost 3m. It has already leaded to so many damages as tidal inundating, rainstorm, water logging, block of navigation under bridge and damage of infrastructure etc. The direct and indirect economic lost is 1.4 and 27.5 billion Euros respectively. Because of these plenty of reasons people should pay more and more attention to it. It is very necessary to invest and research on this subject.

Theory analysis of land subsidence is done in the second part of the report. There are several reasons which can lead to land subsidence. According to Shanghai’s situation, the main reason is the groundwater overexploitation. Time series analysis gives more details about land subsidence of Shanghai in the past. From the time series we can know the policy on controlling this problem is very important. The government should give a good plan. From 1965 to 1990 great achievement has been got. The ground sinks much slower than before because of suitable measures. But during 1990s new character about land subsidence came out. Land sank faster than that of the past 30 years. That is because on one hand ground water extraction is more than before and on another hand more and more high buildings give more loads on the ground. According to some research, 70% of the reason is from the groundwater extraction and 30% of the reason is from the high density of buildings loads in Shanghai.
According to the analysis of land subsidence’s time series and new characters in 1990s some prediction is done:

- Groundwater requirement: new policy and plan indicate that groundwater user will transfer to surface water user in the future. Groundwater will be substituted by surface water. But this can not come into truth very soon. A long period is needed for the replacement. Groundwater is still a good water resource which can not be replaced in the coming 20 or 30 years.

- The deform analysis of the soil shows that the deep and the shallow soil layers will continue consolidating because of the historical effect.

- City construction: the government takes some measures to control the population and density of buildings. But the population in Shanghai is still increasing and more buildings should be done. More loads will be put on the area of Shanghai in the coming 10 years.

All the factors indicate that in the soon future land subsidence will be going on. This problem can not be solved in a short time. Great effort should be done to make the situation better.

Measures evaluation and the existing questions on how to control this problem is given in the last part of the report. Some measures are proved to be valid on solving this problem:
• Artificial recharge: it is the most direct way to solve this problem. Fact proves that ground water artificial recharge is also the most efficient way. Now artificial recharge scheme is done every year.

• Groundwater use plan: the direct reason of land subsidence is groundwater overexploitation in Shanghai. If we do not overuse the groundwater, ground will go down with a very low sinking rate.

• Aquifer layer change of groundwater extraction

• using surface instead of groundwater

• Conservation in application and use of water:

  a. through improvement of irrigation methods, such as change from ditch and furrow of flood irrigation to overhead sprinkler irrigation or to drip irrigation.

  b. through change from crops requiring more water to crops requiring less water.

  c. In urban areas, by recirculation and reuse of treated water by industrial plants

• related rules or laws

Some questions still exist. Now the monitoring system on land subsidence is separated on Yangtze Delta area. Groundwater in that area is a whole system. The lack of cooperation between cities in Yangtze Delta gives much difficulty for solve this problem. Most of the past study is on the shallow soil layer. In order to control this problem better more related researches are needed on the deeper soil layer deformation law.
References


