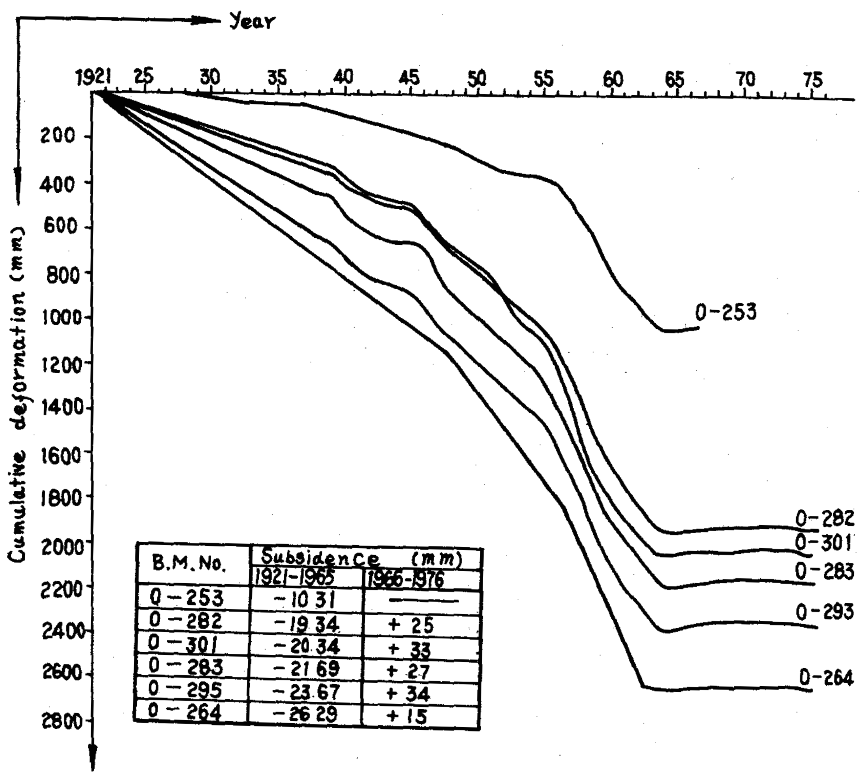
Case History No. 9.2. Shanghai, China, by Shi Luxiang and Bao Manfang, Shanghai Geological Department, Shanghai, China

9.2.1 INTRODUCTION

Shanghai is the largest industrial city in China, standing on the coast of the East China Sea and situated at the front edge of the Yangtze Delta. The elevation[1] of the flat-lying city area is 3-4 metres above sea level. The summer-winter temperature variation is very large. The Whangpoo River and Soochow Creek, both being the outlets of Taihu Lake, are the chief tide waterways of the city.

Land subsidence was first reported in 1921. After liberation, with the rapid development of industrial production, the exploitation of ground water increased, and subsidence continued. The greatest subsidence occurred from 1956 to 1959, at an annual rate of 98 mm. Up to 1965, the maximum cumulative subsidence, as indicated by one of the bench marks in the city area, was as high as 2.63 m (Figure 9.2.1). The area of cumulative subsidence exceeding 500 mm was 121 km^2, forming two plate-shaped depressions in the urban district and affecting the suburban districts, too.

[1]"Elevation" in this paper is based upon the Wusong datum.



B.M. No.	Subsidence (mm)	
	1921-1965	1966-1976
0 – 253	– 10 31	———
0 – 282	– 19 34	+ 25
0 – 301	– 20.34	+ 33
0 – 283	– 21 69	+ 27
0 – 295	– 23.67	+ 34
0 – 264	– 26 29	+ 15

Figure 9.2.1 Cumulative deformation shown by some typical bench marks in the urban area of Shanghai. +, rebound; -, subsidence

After 1963, antimeasures were taken against land subsidence. In 1965, the annual rate of subsidence in the urban area was reduced to 23 mm. From the research results of the preceding period, calculations for the relations among pumpage, water level, and subsidence for the year of 1966 were made in 1965, and the scheme for planning exploitation for the year of 1966 was drawn up. The exploitation of factories followed the plan, and therefore, in 1966, annual rebounding of 6.3 mm occurred in the urban area.

9.2.2 GENERAL GEOLOGICAL CONDITION OF THE OVERBURDEN

In the Shanghai area, unconsolidated materials, about 300 metres thick, of alternating marine and continental facies were deposited on the bedrock during the Quaternary Period. The upper portion of 150 m is composed of clayey soil and sand of littoral and fluvial delta facies; the lower portion of 150 m consists of alternating sand layers of fluvial and variegated clays of lacustrine facies.

Based on the hydrogeological characteristics of the overburden, one water-bearing layer and five aquifers may be identified (hereinafter called aquifers, Figure 9.2.2). The general features of these aquifers are: flat-lying, thick, fine-grained, with small hydraulic gradient and low velocity of ground-water flow. These aquifers are marked by a distinct regularity of lithological changes, finer grained with decreasing thickness from northeast to southwest. Aquitards are widely distributed, only absent in the eastern part, or in local areas along the Whangpoo River, thus bringing about direct hydraulic interconnections between the first, second and third aquifers.

According to its engineering-geological character, the overburden may be divided into 13 layers. Among them are three stiff clay layers below the second aquifer, with fairly high compressive strength; their void ratio is less than 0.70, and their coefficient of compressibility less than 0.025 cm^2/kg. The amount of compression of the layers is comparatively small, as shown in the surveys made over the years. Above the second aquifer are three compressible layers (soft clay layers) with low compressive strength and one dark-green stiff clay layer with fairly high compressive strength. The void ratio of these layers, their water content, coefficient of permeability, coefficient of compressibility, and other principal physical mechanical indices decrease as the depth of the layers increases (Figure 9.2.3).

9.2.3 RELATIONSHIP BETWEEN GEOLOGICAL STRUCTURE AND LAND SUBSIDENCE

According to geological surveys and analytical studies of the observation data, land subsidence principally occurred in the upper layers of the overburden. To present in full the factors causing subsidence, the urban area of Shanghai may be divided into four geological structure areas of land subsidence, based on the different combinations, from the depth of 70 m upward, of three compressible layers and one dark-green stiff clay layer, and based on their relationship with the lst and 2nd aquifers (Figure 9.2.4).

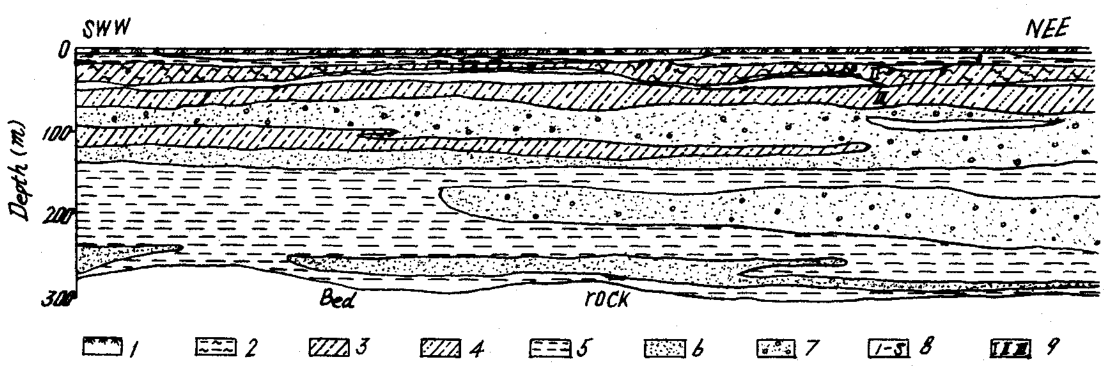


Figure 9.2.2. Geological profile of the urban area of Shanghai. 1, surface soil; 2, muddy clay; 3, muddy clayey loam; 4, clayey loam with sand; 5, stiff clay; 6, sand; 7, sand with gravel; 8, confined aquifer; 9, compressible layer.

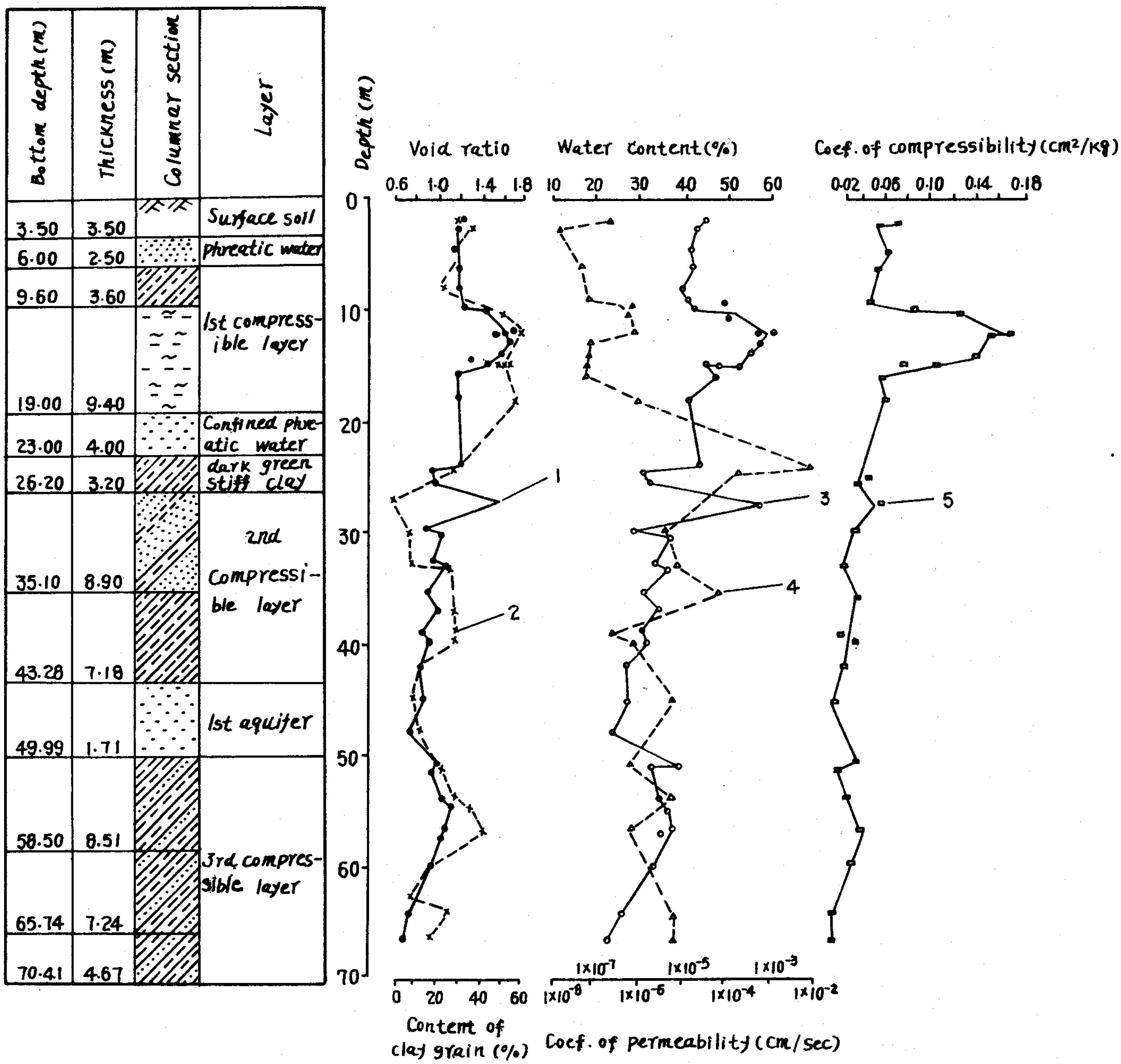


Figure 9.2.3 Variations of main physical-mechanical properties of soil layers with depth. 1, void ratio; 2, content of clay particle; 3, water content; 4, coefficient of permeability; 5, coefficient of compressibility. Legend of columnar section as shown in Figure 9.2.2.

Area No. l(I). Consisting of the lst compressible layer, the dark-green stiff clay layer and the lst and 2nd aquifers. Due to the thin compressible layers and the thick sand layers in addition to the dark-green stiff clay layer, the rebound of land surface was comparatively great after measures were taken.

Area No. 2(II). Consisting of the lst and 3rd compressible layers, the dark-green stiff clay layer and the lst and 2nd aquifers. Owing to the fact that the 3rd compressible layer is comparatively thick, the cumulative subsidence was relatively greater than that in Area No. 1 before measures were taken. However, this is also an area in which the rebound is comparatively great after taking the measures.

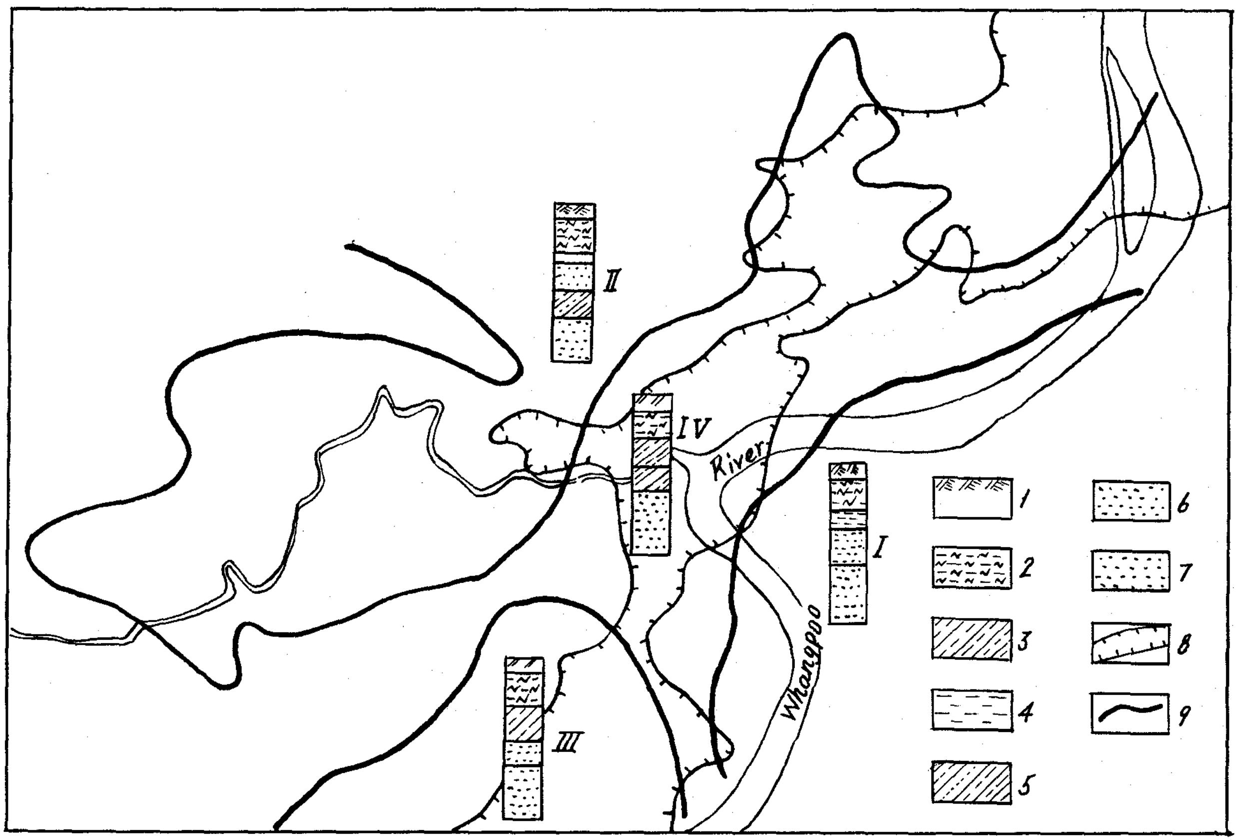


Figure 9.2.4 Relationship between the geological structure and land subsidence in urban area of Shanghai. 1, surface soil; 2, lst compressible layer; 3, 2nd compressible layer; 4, dark-green stiff clay layer; 5, 3rd compressible layer; 6, lst aquifer; 7, 2nd aquifer; 8, slight subsidence within the boundary line, rebound area outside the boundary line; 9, geological structure area and boundary line.

Area No. 3 (III). Consisting of the lst and 2nd compressible layers and the lst and 2nd aquifers. Due to the absence of the dark-green stiff clay layer and the existence of the direct hydraulic interconnection between the lst and 2nd aquifers, the cumulative subsidence was comparatively great before we adopted the methods for improvement. Since the measures were taken, the rate of subsidence has slowed down, though there is still slight subsidence in the lst and 2nd compressible layers.

Area No. 4 (IV). Lying in the central part of the city in a NE-SW direction. This is largely an unexploited and unrecharged area. It comprises the lst, 2nd and 3rd compressible layers and the 2nd aquifer. Since the three compressible layers are thick and there is no dark-green stiff clay layer, the cumulative subsidence had been comparatively great before remedial measures were applied. After we had taken these measures, with the recovery of the ground-water level, the third compressible layer was no longer under compression and began to swell. However, continuation of slight compression of the first two compressible layers has been observed. The geological structure of this area is generally weak.

From the exploration data, we recognized as follows:

1. In areas with the same geological conditions of ground-water exploitation, the amplitude of subsidence varies with the thickness and the compressibility of the compressible layers. Generally, the greater the thickness and the compressibility, the greater the subsidence.

2. The amount of compression of the lst compressible layer depends upon whether the dark-green stiff clay layer is present in the lower part. The subsidence in Areas Nos. 3 and 4, where there is no dark-green stiff clay layer, is greater than that in Areas Nos. 1 and 2 where the dark-green stiff clay layer is present.

3. The rate of compression of the lst and 2nd compressible layers depends upon whether hydraulic interconnection exists between the lst and 2nd aquifers. Therefore, the rate is greater in Area No. 3 where the hydraulic interconnection exists than in Area No. 2 where it does not.

It may be understood that in the course of history, the soil layers have been under the action of fairly low water head. From the relation of preconsolidation pressure of the various soil layers, we know it is equivalent to the action of preloading. Therefore, each layer has its own preconsolidation pressure p_C and preconsolidation ratio $c_r = P_C/P_O$, in which P_O is the overburden pressure). From the depth of the soil layers above 70 m, p_C values are worked out by laboratory tests. We know that the average preconsolidation pressure p_C of the lst and 2nd compressible layers approaches the overburden pressure p_0 of the overlying soil layers. It may be the normal consolidation layer. The 3rd compressible layer is 40-70 m below the surface, and its p_C and c_r increase with depth. The compression of the 3rd compressible layer (over-consolidated) will not occur if the average $(p_C-p_O) \approx 1$ kg/cm^2, i.e., if the drawdown of the ground-water level in the 2nd aquifer does not exceed the average (p_C-p_0) value while the measures controlling land subsidence are being taken.

9.2.4 CALCULATION

According to the mechanism of deformation of the soil layers under the pumping drawdown, it is suitable to apply a one-dimensional equation to calculate the compressive deformation of the soil layers. The drain path of the lst, 2nd and 3rd compressible layers is mainly upward and downward toward the sand layers. Although the ground-water cone exists, yet it has a wider range and small hydraulic gradient. The difference of horizontal water pressure is not great, so the transverse drainage may not be considered.

This principle has been applied to the annual calculation since 1965, and the results have been checked the next year in order to make a comparison with the practice to correct the calculated indices year by year. The calculated value and practice would gradually correlate with each other.

In 1972, according to the elastic-plastic characteristics of deformation of soil layers and the principles of soil mechanics, a physical model was developed. Then through the statistical analysis of a large amount of observed data of deformation, which were influenced by the variation in elevation of the ground-water level under a certain pumping and recharging condition, a simplified mathematical model was developed, in order to get the optimizing numerical solution with computer. Consequently, the forecast and prediction of land subsidence can be made.

Accuracy of calculation has been checked through practice. The period of prediction for scheme calculation is one year. The calculation has been made since 1972. The practice has demonstrated that the maximum error of predicting elevation of water head was ± 0.5 m, when the annual amplitude of water head was less than 6-8 m; the average error of predicting absolute deformation was below 1.7 mm, when the annual average amplitude of deformation was less than 14.3 mm.

9.2.5 MEASURES

The purpose of land subsidence research is to solve the problem of land subsidence; therefore, it is the key of the question to take measures.

The main cause of land subsidence in Shanghai is intensive exploitation of ground water and corresponding drawdown of water level. In order to control land subsidence and to rationalize the exploitation of ground water, the measures for recovering and raising up the ground-water level have been taken on the basis of analysing and researching the laws of land subsidence, according to Shanghai's specific conditions. Preliminary control of subsidence of the urban area has been achieved. The measures taken are chiefly as follows:

1. Restricting and rational usage of ground water.
   Owing to the great disaster made by the land subsidence, in 1963 it was resolved that measures for restricting ground-water exploitation were to be taken by Shanghai Municipal Government. Ground water in Shanghai is mainly utilized to reguate the air and lower the temperature, so the paper, iron and steel industries which do not need cooling energy from the ground water, have changed to using surface water. In addition, some factories have installed refrigeration equipment instead of

using ground water. Cooling energy from this equipment may be equivalent to the cooling energy provided by 200 deep wells. Since 1965, the calculation of land subsidence has been made annually, thus giving the planning exploitation scheme for the next year. And the factories, according to the plan for rational usage of ground water, have taken measures for multiple and comprehensive utilization of ground water.

2. Artificial recharge of ground water.
   The "measures of recharging in winter for summer use and recharging in summer for winter use" have been employed since 1965. The textile mills which need cooling energy can use lower temperatures in summer. From the practice over years, it was proved that after recharging, the temperature of ground water of the 2nd and 3rd aquifers gradually decreased by 6-10° C in comparison with the original, and that of the 4th and 5th aquifers also decreased by 9-10° C. Besides, recharging in winter for summer use and recharging in summer for winter use had the function of raising the ground-water level in order to diminish land subsidence.

3. Adjustments of exploited aquifers.
   Before the measures had been taken, ground water was mainly pumped from the 2nd and 3rd aquifers in the urban area. Although the 4th aquifer contains abundant ground water of fairly good quality, the original temperature is high, so it is not suitable for cooling. Hence the pumpage from the 4th aquifer is small. Due to the irregular distribution of the 5th aquifer and the high temperature of its ground water, pumpage from this aquifer also is small. However, after recharging cool water in winter to these aquifers, the temperature of ground water in them decreases and the water can be used for cooling purposes. Therefore, pumpage from the 2nd and 3rd aquifers has been decreased, and the use of ground water from the 4th and 5th aquifers has been increased. On the other hand, the strength of the soil layer underneath the 3rd aquifer is fairly high, and deformation is not obvious after the exploitation of the 4th and 5th aquifers. This will decrease the rate of land subsidence.

9.2.6 REFERENCES

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