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Risk management of land subsidence in Shanghai

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ABSTRACT

Land subsidence resulting from over-exploited groundwater has become a leading factor restricting the sustainable development of resources, environment, and economy in Shanghai. To design management plans to control the environment geology calamity problems arisen by land subsidence effectively, this research constructed risk index system on the basis of risk source identification of subsidence and then established risk assessment model. The risk index system is composed of hazardous conditions and vulnerability of land subsidence. Results from comprehensive consideration of the model calculations, subsidence distribution and local socio-economic trends showed that the controlling district of land subsidence in Shanghai can be divided into three subsidence—primary control zone (Zone Ⅰ), second control zone (Zone II), and normal control district (Zone III), corresponding with a high, moderate, low subsidence risk, respectively. On the basis of Shanghai urban and rural planning, the control target scheme of land subsidence with each zone in the future, different groundwater, resources management schemes are put forward, which mainly refer to control groundwater exploitation, to perform artificial recharge and to strengthen construction of recharge wells.

Keywords: Land subsidence; Risk index system; Risk management; Subsidence control zone

1. Introduction

Shanghai is one of the cities which have suffered serious land subsidence in China. This land subsidence was probably caused by structural and historical reasons. The Shanghai area, within 300 m underground, is composed of Quaternary loose debris, including soft clay and sands in less than 75 m, as well as hard clay and sand layers under 75 m. Fig. 1 shows the underground structure of this area [1]. During the early 1960s, the annual withdraw of groundwater exceeded $2 \times 10^8\,m^3$, which generated a regional groundwater depression cone in center of the city. The excessive-extraction greatly accelerated land subsidence, which sometimes can reach a sedimentation rate of more than 100 mm in one cycle year. After the 1960s,

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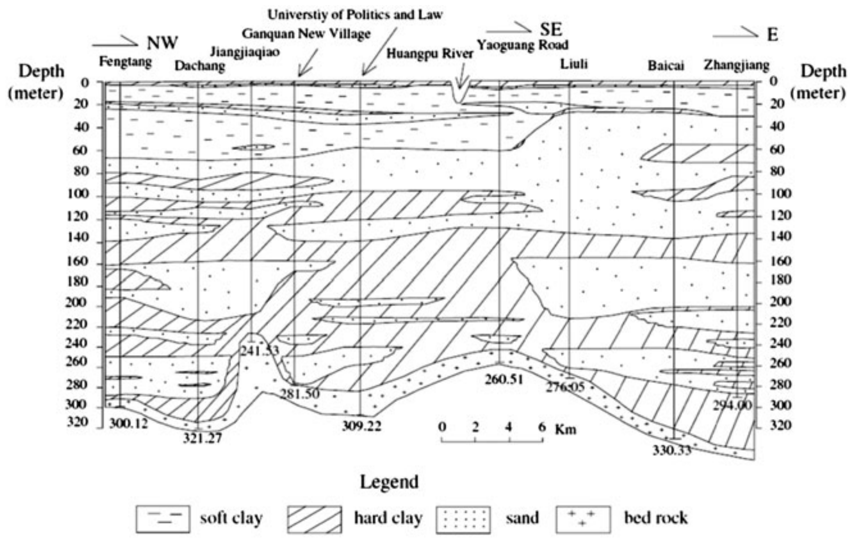

Fig. 1. Schematic stratigraphic section in Shanghai.

Shanghai government took great effort to curb land subsidence, such as reducing groundwater pumping, adjusting patterns of underground exploitation, and implementing artificial recharge [2–5]. These measures have gotten exciting returns, for example, the annual sedimentation rate in 2010 was controlled in less than 7 mm, with extraction amount of $1970 \times 10^4\,m^3$ and groundwater recharge of $1892 \times 10^4\,m^3$. However, there are still many problems existing in practice, for example, uneven distribution between pumping and recharge. One of the solutions to solve above problems is to take differentiated measures on different partitions. But in practical work, the lack of partition rules and proper zoning methods puzzled plenty of field engineers, which made it difficult to develop scientific management on land subsidence zoning.

At present, risk assessment is widely used in controlling and management for geological disasters such as tunnels, landslides and mudslides [6–9]. In the field of land subsidence, it mainly focused on theoretical research. However, risk assessment can effectively identify risk factors and give reasonable evaluation results by scientific calculation [10]. Then, different zones can be partitioned based on assessment results. So risk assessment is a good choice to solve the field engineers' problems above.

In this paper, a system for the risk assessment of land subsidence was established. It took two aspects into account comprehensively: hazardous conditions and vulnerability of land subsidence. Based on identification of various factors, evaluation index was calculated by mathematical methods, from which the evaluation results derived. Combining the results with socio-economic development in Shanghai, the groundwater management scheme for land subsidence was raised up, which would provide a theoretical and technical support for the controls of land subsidence in Shanghai.

2. Identification of risk factors

Risk of geological disaster for land subsidence depends mainly on two factors: hazardous risk of land subsidence and economic vulnerability of human society [11]. The hazardous risk, also defined as Hazard factor (H), includes geological structure (e.g. aquifer distribution, thickness of soft soil and its structure), geomorphology condition (e.g. landform types and terrain elevation), and human geological activities (e.g. housing construction and groundwater exploitation). Generally, the stronger the hazard factor is, the more intensely the disaster occurs, which resulting in higher risk of land subsidence. The second condition, also defined as Vulnerability factor (V), is composed of the resilience and recoverability capacity to geological disasters in affected areas for human life and various economic activities, including population density, living environment, type of land use, investment in disaster prevention, mitigation, and others. Generally, the higher the density of population and property is, the greater the loss caused. The factors of Hazard and Vulnerability together determine the degree of risk of geological disaster for land subsidence. Therefore, the two factors are labeled as two essential elements in Risk Assessment System.

Based on the mechanism of land subsidence, development conditions, monitoring results and other factors [12–15], Shanghai selected four key indicators to evaluate the risk of the Hazard factor: frequency of land subsidence, disaster intensity, sedimentation rate and terrain elevation. Meanwhile, the vulnerability factor mainly related to socio-economic statistical indicators (population density, GDP, proportion of construction, etc.), infrastructure which was greatly affected by land subsidence (flood control wall, railway, water supply network, elevated road), and input for disaster control (monitoring and control facilities). These were illustrated in Fig. 2.

3. Risk assessment of land subsidence

3.1. Assessment of hazard factor

The conceptual model is as follows, firstly to take separate assessment for each indicator; and secondly to establish related models and then to get a comprehensive assessment.

At present, the common methods used for risk assessment includes the analytic hierarchy process (AHP) [16], the fuzzy comprehensive evaluation (FCE) [17], the gray clustering method [18]. Because there are plenty of difficult quantitative indicators in this assessment, we need to select a suitable method which could handle these complex and tough quantitative problems. Obviously, the AHP is the one. However, it is very important to fix the weighs for all types of impact factors in hazard assessment of land subsidence. It is directly related to the rationality and authenticity of results. When we use the normal AHP to evaluate weigh-matrix, it is very difficult to judge the consistency of matrix and hard to meet requirements of the convergence speed and accuracy of the solutions, which lead to uneasiness for determine the index weights. But now an improved fuzzy AHP was proposed to solve above problems, and it was employed to determine the weights of risk assessment of land subsidence.

The principle of improved fuzzy AHP is to change reciprocal judgment matrix to fuzzy consistency judgment matrix and use normalizing rank aggregation or root-mean-square method in combination with eigenvector method. Thus, the evaluation results of hazard factors could be calculated.

$$H_{\text{risk}} = \sum_{i=1}^{4} W_i N_j \quad (j = 1, 2, \ldots, n) \tag{1}$$

Where H_{risk} is evaluation index for geological hazard; W_i is the weight; N_j is index for each factor.

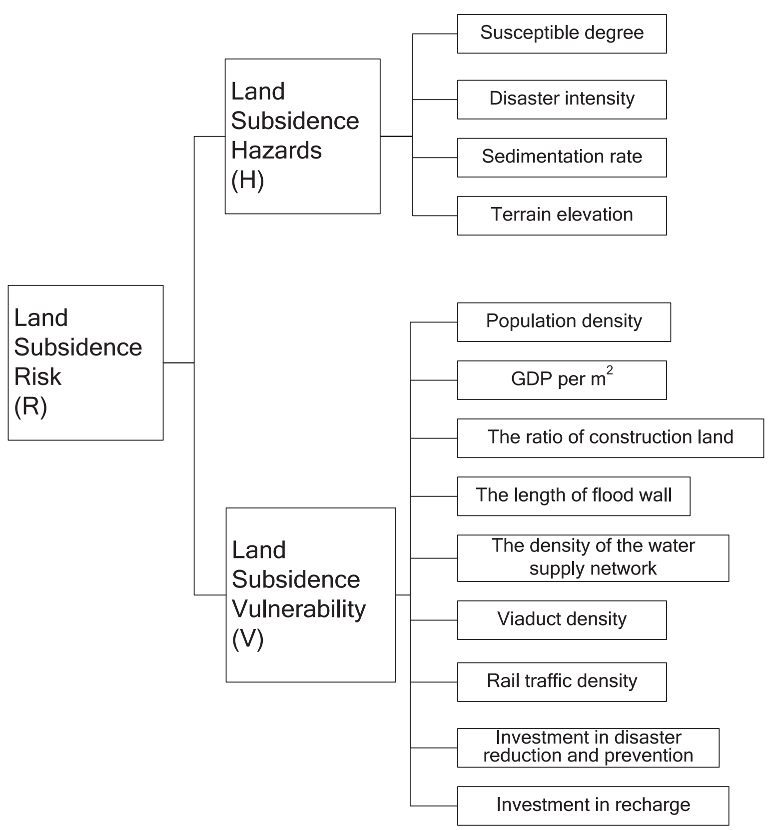

Fig. 2. Index system of risk assessment for land subsidence in Shanghai.

In practice, the evaluation calculation was based on MAPGIS platform. It took comprehensive consideration of all influencing factors and extracted basic property of each factor to establish a hazard-assessment model for land subsidence with the help of GIS's powerful spatial-modeling capability. The results were displayed in Fig. 3.

From Fig. 3, Shanghai mainly lay in the moderate-risk zones. However, there are also some dotted high-risk zones, such as the urban area and little parts of Jiading District and Jinshan District. The low-risk zones are located mainly in Fengxian District and Qingpu District, which have well-developed geological environment and low speed for land subsidence. In addition, the three islands, which administratively belong to Shanghai, are located in moderate-risk zones as well.

3.2. Assessment of vulnerability factor

The capacity to bear land subsidence is unequal in different entities, as well as recoverability after the disaster. Therefore, the assessment for vulnerability factor includes two aspects: sensitivity analysis and study on disaster-bearing capacity. It reflects the right relationship between human activity, socio-economic development and the natural environment.

Because of convenience to get data from administrative units (municipal districts and counties), it is prone to zone the Shanghai Area into different parts based on administrative regions and characterize the vulnerability by socio-economic statistical indicators. Vulnerability factor mainly related to socio-economic statistical indicators (population density, GDP, proportion of construction, etc.), infrastructure that was greatly affected by land subsidence (flood control wall, railway, water supply network, and elevated road), and input for disaster control (monitoring and control facilities). The method of FCE was selected for zoning, while index value method was selected to determine the weight, which can minimize human disturbance. The procedure is as follows:

Fix the factor weighting-matrix A. The weighting-matrix A, where $A_{1\times n} = (a_1, a_2, \ldots, a_n)$, is determined by grading of evaluation factors. The normalized weight $a_i (i = 1, 2, \ldots, n)$ is calculated as follows:

$$a_i = \frac{c_i/s_i}{\sum_{i=1}^{n} c_i/s_i} \tag{2}$$

where c_i is the measured value of factor $i; s_i$ is the standard value of factor i.

Establish a fuzzy relationship matrix R. On the basis of calculation of factor-membership functions at

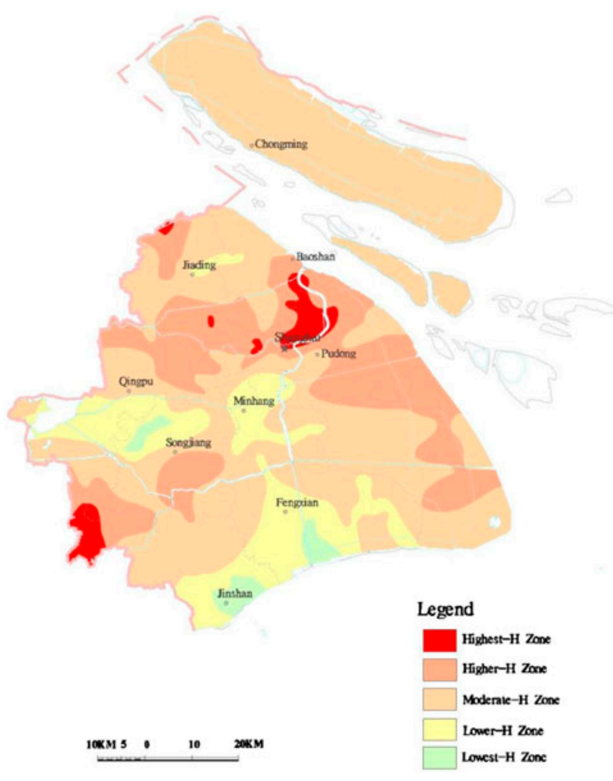

Fig. 3. Hazard evaluation (H) of land subsidence in Shanghai.

all levels, a fuzzy relationship matrix is established for each factor evaluation:

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ r_{21} & r_{22} & \dots & r_{2m} \\ \dots & \dots & \dots & \dots \\ r_{n1} & r_{n2} & \dots & r_{nm} \end{bmatrix} \quad (3)$$

Calculate the FCE matrix B. Based on the principle of fuzzy transformation, matrix B can be computed by $A \times R$, where the algorithm is the weighted average fuzzy synthesis.

$$b_j = \sum_{i=1}^{n} (a_i \wedge r_{ij}) = \min\left(1, \sum_{i=1}^{n} a_i r_{ij}\right)$$
$$j = 1, 2, \dots, m \quad (4)$$

Based on the monitoring data from various districts in Shanghai, factor weights were calculated by the method of FCE, and finally, assessment results for vulnerability were obtained (Fig. 4).

The results showed good relevance between regional economic development and extent of land subsidence. And the vulnerability factor of land subsidence was divided into five levels. The first level had highest vulnerability, mainly including the central part of Shanghai whose economy was mostly developed. The second level had higher vulnerability, mainly including Gaoqiao, Zhangjiang, Tangqiao, etc. they all formed regional subsidence depression, with higher socio-economic indicators (GDP per m^2, proportion of construction land and density of municipal facilities). The third level had moderate vulnerability, mainly including Baoshang District and Minhang District, which possessed medium socio-economic indicators. The fourth level had relatively low vulnerability, mainly including Songjiang District, part of Pudong District and Jiading District. The three districts possessed relatively low socio-economic indicatorsand were subject to land subsidence to a lesser extent. The fifth level had the lowest vulnerability, mainly including Fengxian District, Chongming County, Jinshang District and Qingpu District. They are located at the edge of Shanghai, and its economic development is relatively backward.

3.3. Risk assessment

On the basis of comprehensive analysis for all data, the value of hazard could be calculated according to evaluation results of hazard factor, and the hazardous level could be rated. Similarly, as in the

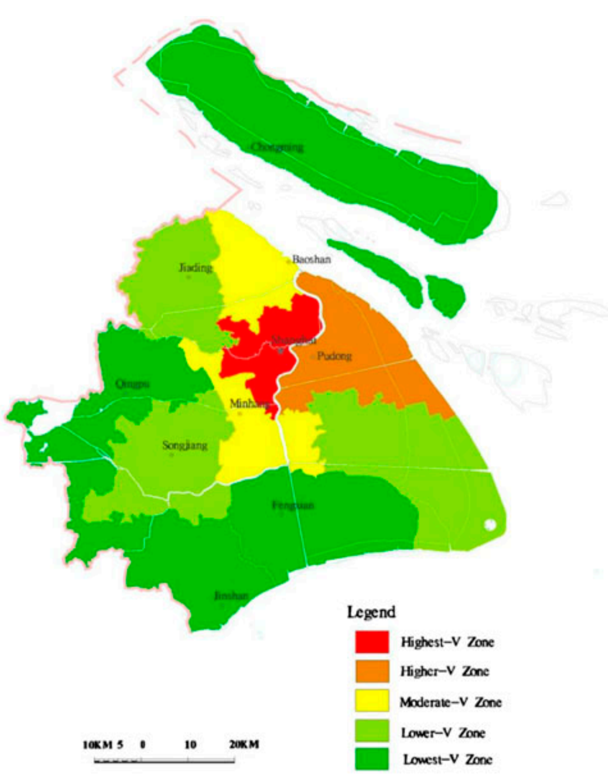

Fig. 4. Vulnerability Evaluation (V) of land subsidence in Shanghai.

same case, the value of vulnerability and vulnerable level could be obtained according to evaluation results. Then, the risk level may be determined by using the following formula: $R = H \times V$, Where R is the risk level, H is the hazardous level, and V is the vulnerable level. During the process of quantitative evaluation, the value of levels (H and V) ranged from zero to one, and five grades were partitioned: very low (VL), low (L), medium (M), high (H), very high (VH), and the corresponding values are (0, 0.2] (or $\leqslant$0.2), (0.2, 0.4], (0.4, 0.6], (0.6, 0.8], (0.8, 1.0] (or $\geqslant$0.8), respectively. In the light of above formula, R was also partitioned into five grades, and the corresponding values are [0, 0.04] (or $\leqslant$0.04), (0.04, 0.16], (0.16, 0.36], (0.36, 0.64], (0.64, 1.0] (or $\geqslant$0.64), respectively. After that, the zoning map for risk could be drafted on the basis of risk classification for all areas. Fig. 5 illustrated the evaluation results of land subsidence in Shanghai.

4. Risk control of land subsidence

In order to scientifically control land subsidence, Shanghai was divided into three major risk-control districts on the base of the risk-assessment map and administrative division of Shanghai. Three districts were graded by risk value (Fig. 6): the primary control zone (Zone I), the secondary control zone (Zone II), and the normal control zone (Zone III). Every zone has its own characteristics and situation of land subsidence and would implement different plans for groundwater resources management in the next few years.

4.1. The primary control zone (Zone I)

Due to different time of land subsidence, Zone I mainly was divided into two subzone: Zone I_1 (the urban district) and Zone I_2 (Pudong District and Hongqiao Business District). In Zone I_1, serious land subsidence disasters had occurred, and situation of flood control was grim; extensive engineering construction lead to uneven land subsidence, which gave a great impact on sage operation of public traffic, for example, rail transport. In Zone I_2, land subsidence presented worsening trend, especially in Hongqiao and Sanlin (in Pudong District), which posed a great impact on rail transportation and maglev train operation.

In order to minimize the impact of uneven subsidence and to control the average annual amount of land subsidence in less than 7 mm (I_1) or 10 mm (I_2)

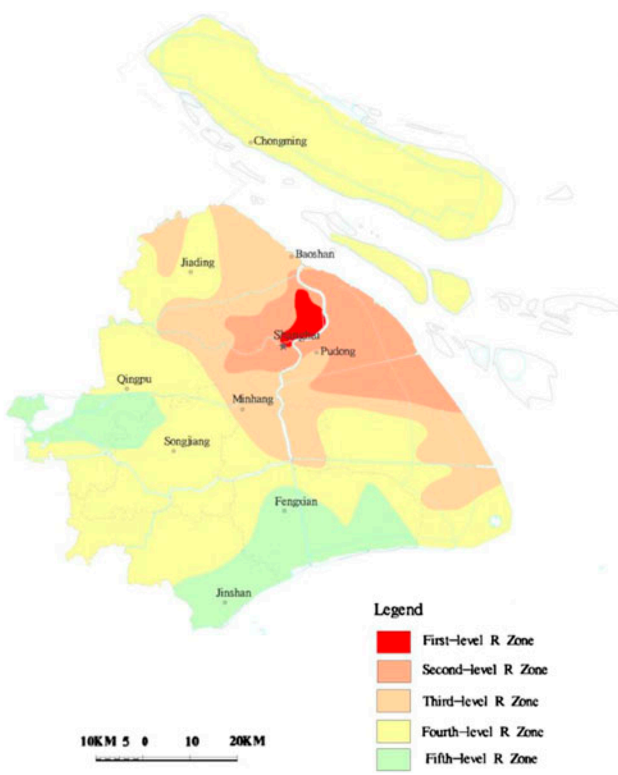

Fig. 5. Risk evaluation (R) of land subsidence in Shanghai.

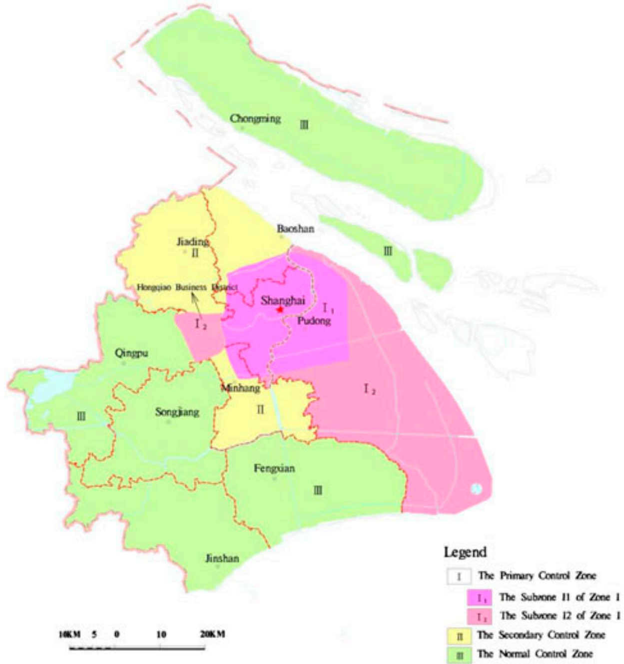

Fig. 6. Risk management zoning of land subsidence in shanghai.

by the end of 2015, lots of measures should be implemented. For I_1, it should be to control annual exploitation in less than 1,000,000 m^3, to perform artificial recharge, to ensure the volume to surpass 13,500,000 m^3/years, and to strengthen construction of recharge wells in the shallow and deep confined aquifers; for I_2, to control annual exploitation area in less than 4,300,000 m^3, to perform artificial recharge and to ensure the volume would surpass 2,500,000 m^3 per year, to optimize groundwater exploitation, and to take scientific construction of recharge wells in the fourth and the fifth confined aquifers.

4.2. The secondary control zone (Zone II)

Zone II mainly included Baoshan District, Jiading District and Minhang District. At the moment, the exploitation of groundwater in this zone is in low level, and the risk of land subsidence is rated as moderate zone. The control measures are listed as follows: to control annual exploitation area in less than 5,000,000 m^3, to perform artificial recharge and to ensure the volume would surpass 2,200,000 m^3 per year and to take scientific construction of recharge wells in the fourth and the fifth confined aquifers.

4.3. The normal control zone (Zone III)

Zone III mainly included Fengxian District, Songjiang District, Qingpu District and Chongming County. In these areas, constructions are in low intensity, and the amounts of subsidence indicated are relatively small.

The major measures should be taken to control the annual exploitation area in less than 9,700,000 m^3, to make sure that the artificial recharge volume surpassing 4,800,000 m^3 per year, and to accomplish the scientific development of recharge wells in the fourth and the fifth confined aquifers.

5. Conclusions

This research constructed risk index system on the basis of risk source identification of subsidence in Shanghai region and then established the risk assessment model. The risk index system is composed of two aspects, hazardous conditions and vulnerability of land subsidence. According to the results of risk assessment, the risk degree of land subsidence was partitioned into five grades: very low (VL), low (L), medium (M), high (H), very high (VH). In order to scientifically control land subsidence, Shanghai was divided into three major risk-control districts on the base of the risk-assessment map and administrative division of Shanghai. Three districts were graded by risk value: the primary control zone (Zone I), the secondary control zone (Zone II), and the normal control zone (Zone III). In Zone I, serious land subsidence disasters had occurred. In Zone II, the exploitation of groundwater in this zone is in low level, and the risk of land subsidence is rated as moderate zone. In Zone III, constructions are in low intensity, and the amounts of subsidence indicated are relatively small. Difference groundwater management measures are proposed to control land subsidence in the three zone, which mainly refer to control groundwater exploitation, to perform artificial recharge, and to strengthen the construction of recharge wells.

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