THE APPLICATION OF REMOTE SENSING AND GIS IN THE STABILITY EVALUATION OF GOAVES

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ABSTRACT:

From September 2006 to April 2007, according to requirement of Jincheng Planning Department, the authors had finished the goaf survey of coal mines and geological hazards around Jincheng city by means of multi-temporal airborne(three times, 1974, 1999, 2005) and Quickbird images (from 2002 to 2005), combined with field survey and image processing technology to extract goaf information.This paper introduced a method for evaluating the stability of goaves around Jincheng city with remote sensing and GIS. The approach included four steps: 1) to collect the basic information as much as possible, such as all kinds of maps related to coal mining, and remote sensing investigation results, 2) to quantify all the basic information, 3) to evaluate the stability according to some regulations, and get the result maps, 4) to establish an information system for the local government. After half a year's application, the results demonstrated that the appraisal of stability to the goaf areas could meet the requirement of City Planning Bureau, and had already been used in urban planning. However, for the limitation of remote sensing technology, in addition with the dynamic change of goaf distribution range caused by mining, people should also adopt geophysical prospecting and borehole surveying to confirm the situation and stability of goaf for building design and the processing of building foundation on the basis of general survey.

1. INTRODUCTION

China has a long history of coal mining. Many kinds of geological disasters such as huge goaf subsidence, collapse and cracks accompany the exploitation of coal resources. As was investigated(He, 2002), 93.19% of collapsed area is caused by coal mining. The depth of the most collapse reaches 70%~80% the thickness of the exploited coal seam, or even 90%, and the collapsed area is about 1.12 times of its exploitation area, and the collapse rate of each digging ranks from $0.11hm^2$ to $0.13hm^2$ per 10,000 tons of coal, $0.127hm^2$ on average.

A number of methods can be used for goaf investigation, and generally there are remote sensing, ground-penetrating radar(Ren, 2005), Rayleigh wave method (Chang, 2002; Gao, 1995), drilling exploration, high-density resistivity method (Li, 2006; Wang, 2004), seismic imaging, as well as 3D laser. The choice of the methods depends on users' purpose and their requirement of accuracy.

In August 2006, we completed a project of goaf survey around Jincheng city (Shanxi province, China) by airborne and space borne remote sensing image interpretation and analysis, as well as field investigation. We had finished a survey and obtained the number of local coal mines and locations, gob areas, and the developing characteristics of collapses and cracks. By GIS, we made a preliminary evaluation to the stability of goaves and determined the intensity of collapse above goaves.

2. REMOTE SENSING INFORMATION EXTRACTION OF COALMINE AREAS AND GROUND SURVEY

2.1 Remote Sensing Interpretation of Small Collieries

Airborne images taken in 1974, 1999 and 2005, as well as Quickbird image from 2002 to 2005 were collected. For the image in 1974 was too early, there were only several small coalmines in it. In the image of 1999 there were much more small coalmines, but the scale of the image was too small, and some smaller coalmines' locations and ranges couldn't be determined effectively. The air photos in June 2005 had dense vegetation coverage，and collapses were seriously interfered with plant, but they reflected the black deposits such as coal stacks, coal washing spots and abandoned small coalmines clearly. Since 1998, the local government had launched a series of actions against small mines, such as closure, abortion, combination, and rectification, making lots of small coalmines completely disappear from the ground. But in Quickbird image before 2005, the distribution of almost all coalmines could be seen, (figure 1), even those coalmines without any ground traces in 2006 were still clear in Quickbird image.

To interpret surface collapses, cracks and small coalmines from remote sensing images we mainly depend on image features (i.e. spectral features: tone and colour) and spatial characteristics (shape, size, shadow, texture, graphics, location and layout). Comprehensive analysis and reasoning from a variety of related non-remote sensing information (such as topographic maps, known distribution maps of mined area, age of gob areas，survey maps of geological disasters in the past, etc.) combined with change rates of surface elevations also played an important role. In the interpretation process, the use of stereoscopy interpretation and image processing improved the visual effects of the images and the precision of results effectively.
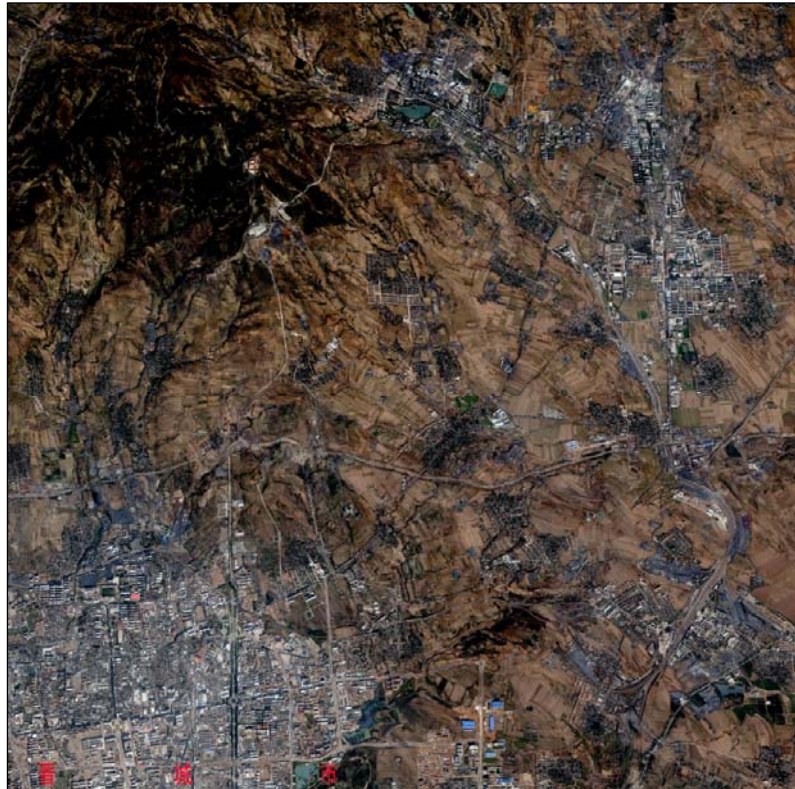
Legend | small mine | water body | bare ground | urban area | green land

Figure 1. Quickbird Image of the northeast part of Jincheng city, the grey areas are suspected small coalmines
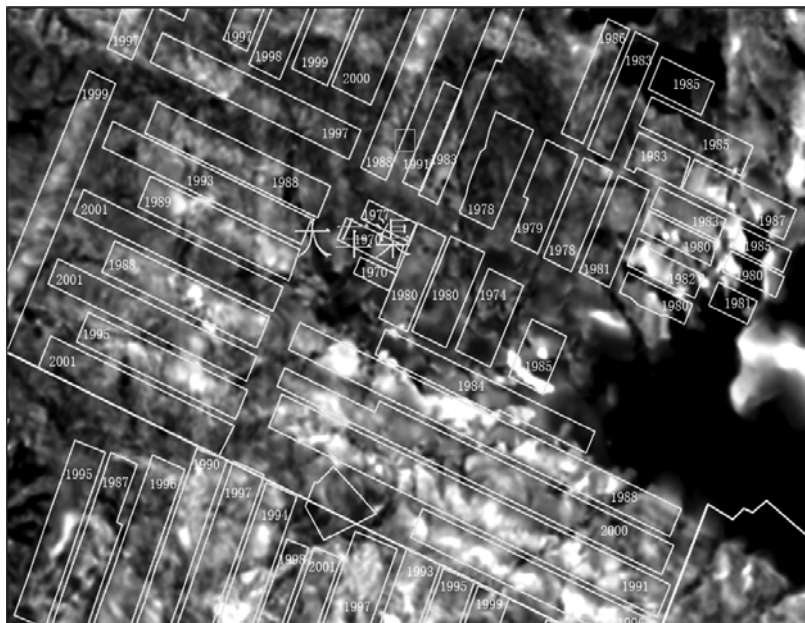

Figure 2. The sketch of ground collapse intensity and gob area in Phoenix Mountain coalmine, the numbers are the years of mining, the brighter the tone, the greater the surface subsidence intensity.

2.2 Determine the Extent of Surface Subsidence with DEM

Digital Elevation Model (DEM) is an effective means to mark the subsidence(Wang, 2004) and detect ground changes [8]. In order to redisplay the terrain changes, we produced two digital elevation models of 1983 and 2006, and then got a map of surface subsidence intensity. Figure 2 reflects the results of the overall changes of the ground surface within a period of 23 years. These changes included ground uplift and downfall caused by coal mining, municipal construction projects, water conservancy, farmland transformation, reclamation of collapsed lands, natural weathering and erosion, river transportation and deposition. The subsidence intensity had stronger relationship with mining within the regions with fewer ground human activities(Liu, 2005). Figure 2 also shows the completed coal working faces and the years of completion of the big coalmines in the region. It is shown in the map that distinct ground subsidence occurred above almost all the mined working faces. According to field monitoring, the ground surfaces above the goaves subsided at the fastest speed within the first three years after coal was dug out, then the speed lowered significantly, and the subsidence amount maximized approximately 15 to 20 years after digging and the subsidence process probably came to a halt. Therefore, digging areas older than 15 years were hard to be found only by the change extent of elevation.

Table 1 indicates the linear, exponential and logarithmic regression analysis result of ground collapse intensity with the years after digging.

regression analysis	formulas	Correlation coefficients	Standard errors(m)
linear	$Y=1.881+0.052X$	0.529	0.506
exponential	$Y=0.402e^{-0.250/x}$	0.309	0.565
logarithmic	$Y=1.807+0.622\lg X$	0.441	0.535
explanation	X：years after digging，Y collapse extent (m)，totally 129401 pixels (8×8m) used in analysis of working face after digitizing, covering 1035208m^2		

Table 1. The form of correlation analysis of ground collapse intensity and the years after digging

Figure 3 presents the form's of the three functions. From the theoretical analysis, the exponential formula should best represent the relationship between collapse extent and the time of sinking, however, the formula has biggest error because the subsidence extent have close relation with the stopping rate, deep-thickness ratio of coal seam, mechanical strength of the roof rock, length and width of working face, and latter reconstruction of the ground surface, etc. Therefore, the sketch of ground collapse intensity acts only as a reference map for comprehensive evaluation.
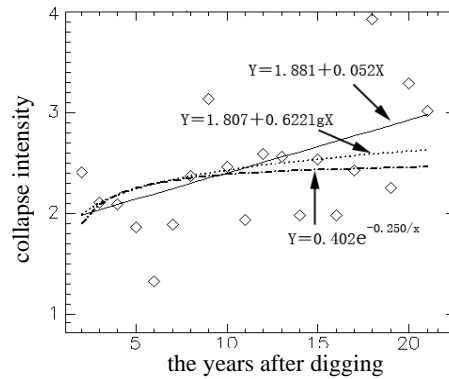

Figure 3. The sketch of ground collapse intensity and the years after digging

2.3 Field Investigation

Overall surveys for distribution of small coalmines, goaves, ground cracks, water table changes, currently harmful situation and their development trend caused by ground collapse above the goaves under the region had been done during field investigation, which also helped verify the results of remote sensing, discover and collect various basic geological disaster information in the area, and fill out questionnaires. Positioning and taking pictures of small coalmines, goaves, ground cracks provided basic information for the stability evaluation of goaves and information system establishment.

Goaves were divided into two types based on information of coalmines, remote sensing images, changes of ground elevation intensity, field survey data, as well as topographical maps:

① the precise mine goaves of big coalmines (based on the layout maps of working face)

② infered goaves of small collieries: formula for area calculation of speculated goaves:

Area = (average annual output × length of service) / (coal density × coal seam thickness × stoping rate)

3. EVALUATION TO THE STABILITY OF GOAVES

On the basis of field investigation and remote sensing interpretation in addition with collected information and ground collapse intensity, we did comprehensive analysis to determine the number, locations and distribution range of coalmines in the region, and preliminarily determined the locations, sizes, development characteristics and the distribution law of the goaves of coalmines, mining collapses and cracks. Researches on the correlation of goaves, mining collapse and cracks made a preliminary evaluation and forecast to stability development characteristics of goaves and mining collapse.

According to "Code for investigation of geotechnical engineering", factors that should be included for evaluation of goaf stability are: years after digging, deep-thickness ratios of the coal seams, lithology of coal seam's roof rock, number of layers of mined coal seams, distribution density of small coal mines, surface slope, and ground collapse intensity. Jilin Wang (2005) used fuzzy comprehensive evaluation(Wang, 2005)

method according to many of the factors mentioned above to evaluate stability of coalmine goaves, and in this paper we calculated the risky coefficient of each point in the region by application of comprehensive evaluation model and according mainly by the factors such as years after digging, the number of layers of mined coal seams, coal seams deep-thickness ratio, lithology of coal seam's roof rock and the distribution density of small coal mines, and then divided the stability of the goaves into three levels which are: less stable, unstable, and extremely unstable with relevant analysis.

3.1 Data Preprocessing

In order to make comprehensive evaluation of the stability of goaves, firstly the relevant information must be digitized and pretreated to make maps of various factors.

1)   The factor of years after exploitation

All information is from the digging time of the working face. Experience demonstrates that, from the time of current moment, 15 years can be used as a cut off point of time, for more than 15 years, the goaf has tended to be stabilized, and the shorter the time, more unstable the goaf is. The instability coefficient (Ins_1) conversion formula of the years after digging of goaf is:

If ($year > 15$) then $year = 15$
$Ins_1 = (15\text{-}year) / 15$

2) The factor of depth-thickness ratio of mined coal seams

The thicknesses and depths of coal seams from drill holes and field investigation of small coalmines were utilized to work out the depth-thickness ratio sketch (dtr) with interior interpolation of trend surface. And then dtr was transformed to an instability factor map (Ins_2) with the following formula:

If ($dtr > 30$) then $dtr = 30$
$Ins_2 = (30\text{-}dtr) / 30$

3) The factor of instability of the roof litho

There are great differences among the hardness of roof lithology of coal seams $3^{\#}$, $9^{\#}$ and $15^{\#}$. Coal seam $3^{\#}$ lies beneath the earth surface relatively shallower with sandstone, mudstone, and loess covering on. The roof of coal seam $9^{\#}$ is multi-stories of limestones interbedded with sandstones. The roof of coal seam $15^{\#}$ is mainly hard limestone. The instability factor of the roof of coal seam $3^{\#}$ is given 1.0, and that of $9^{\#}$ and $15^{\#}$ were given 0.7 and 0.5 respectively.

$Ins_{31} = 1.0$ (coal seam $3^{\#}$)
$Ins_{39} = 0.7$ (coal seam $9^{\#}$)
$Ins_{315} = 0.5$ (coal seam $15^{\#}$)

4) The factor of the number of mined coal seams

We determined the number of mined coal seams of each place according to the locations of outcrops of coal seams, and divided instability factor into single-layer and double-layer.

$Ins_4 = 1.0$ (single-layer of coal seam)
$Ins_4 = 1.2$ (double-layer of coal seams).

5) The density of small coalmines

The number of small coalmines within the diameter of 1 km of each point was selected as the density factor. The greater the value, the more small coalmines distributed nearby, and the stronger the damage of the surface and underground is, and the higher the instability of the place is. According to statistics, the maximum value in density map of the small coalmines is 51. The instability map (Ins_5) of small coalmines was obtained with the Normalization formula:

$Ins_5 = den/51$

where den stands for the density of small coalmines of each point in the region.

3.2 Comprehensive Calculation of the Stability Coefficient

The five factors mentioned above are the basis of comprehensive evaluation, and comprehensive evaluation method is to calculate the general instability （Ins_T）:

$$Ins_T = \sum_{i=1}^{5} Ins_i \times P_i \qquad (1)$$

where Ins_i: the five factors (raster/vector map) mentioned above
P_i: the weight of each factor. The weights of Ins_1 to Ins_5 are 0.4, 0.2, 0.1, 0.1, 0.2 respectively.

The result is shown in figure 4, which demonstrates the brighter area in the map has "may be" higher instability.
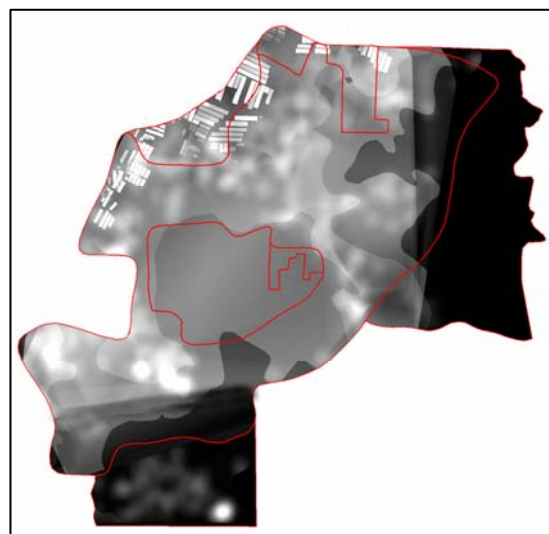

Figure 4. The sketch of stability coefficient, the darker the picture shows, the higher stability coefficient is.

3.3 Stability Classification of Goaves

The principles for stability classification of goaves are:

1) Use Figure 4 as a fundamental map to determine the stability of goaves.

2) According to clause 4.5.5 of "Code for investigation of geotechnical engineering (GB 50021-2001)", the current and future goaves, whose eigen values of ground surface moves and deformation should be calculated and predicted. The values should be calculated for the prediction of gentle slope (dip_angle less than 25°) coal seams. A certain distance is added outward to the exact margin of each goaf with the formulas in table 2, and the unstable district is determined.

Items	Maximum deformation	Deformation at any point（x）
Subsidence (㎜)	$W_{max} = \eta m$	$W(x) = \dfrac{W_{max}}{r} \int_x^\infty e^{-\pi\left(\frac{x}{r}\right)^2} dx$
Slant T(㎜/m)	$T_{max} = \dfrac{W_{max}}{r}$	$T(x) = \dfrac{W_{max}}{r} e^{-\pi\left(\frac{x}{r}\right)^2}$
Curvature K(㎜/m^2)	$K_{max} = \pm 1.52 \dfrac{W_{max}}{r^2}$	$K(x) = \pm 2\pi \dfrac{W_{max}}{r^3}\left(\dfrac{x}{r}\right) e^{-\pi\left(\frac{x}{r}\right)^2}$
Horizontal Shift U(㎜)	$U_{max} = bW_{max}$	$U(x) = bW_{max} e^{-\pi\left(\frac{x}{r}\right)^2}$
Horizontal deformation ε(mm/m)	$\varepsilon_{max} = \pm 1.52 b \dfrac{W_{max}}{r}$	$\varepsilon(x) = \pm 2\pi b \dfrac{W_{max}}{r}\left(\dfrac{x}{r}\right) e^{-\pi\left(\frac{x}{r}\right)^2}$

Table 2. The formulas to predict ground surface moves and deformation

where η: subsidence coefficient, relevant to the dip_angle of coal seam, mining methods and roof management methods, preferably from 0.01 to 0.95

m: thickness of the mined coal seam (m)

r: main influence radius (m)

b: horizontal move coefficient, preferably from 0.25 to 0.35

W_{max}: stands for the greatest deformation, with the formulas shown in table 3.

Item	invention organization	
	Beijing coal mine research institute	Tangshan coal science institute
Maximum subsidence	$S_0 = q_0 D$	$S_0 = q_0 D$
Maximum slant	$I_0 = S_0/r$	$I_0 = 0.9 S_0/L$
Maximum Curvature	$K_0 = \pm 1.52 S_0/r^2$	$K_0 = 1.39 S_0/L^2$
Maximum Horizontal displacement	$U_0 = bS_0$	$U_0 = 0.9 S_0/L$
Maximum Horizontal deformation	$\varepsilon_0 = \pm 1.52 b i_0$	$E_0 = 1.39 K_I S_0/L^2$

Table 3. The empirical formulas to calculate the maximum deformation of the earth's surface near a goaf of mine

Where S_0: Maximum subsidence (mm)

i_0: Maximum slant mm/m

K_0: Maximum Curvature (mm/m^2)

ε_0: Maximum Horizontal Deformation (mm/m)

q_0: Subsiding rate; between 0.02~0.8, depending on the method of the management of coal seam's roof

r: main influence radius (m), $r = H/\tan\beta$

H: mining depth (m)

β: Traveling angle, usually 1.5~2.5

L: Distance from the centre of subsiding (the maximum subsiding point) to the knee point of subsiding curve) (m)

D: Depth of mining (m)

b: Horizontal move coefficient, usually b＝0.3

K_I coefficient, usually 10~12.

3) Based on figure 4 and the change extent of DEM, collapse intensity, ground movement and deformation intensity, a classification map of stability was done manually, which included: extremely unstable district (I), unstable district (II), and less unstable district (III). Districts with the same instability were further numbered as I-1, I-2, etc, see figure 5.
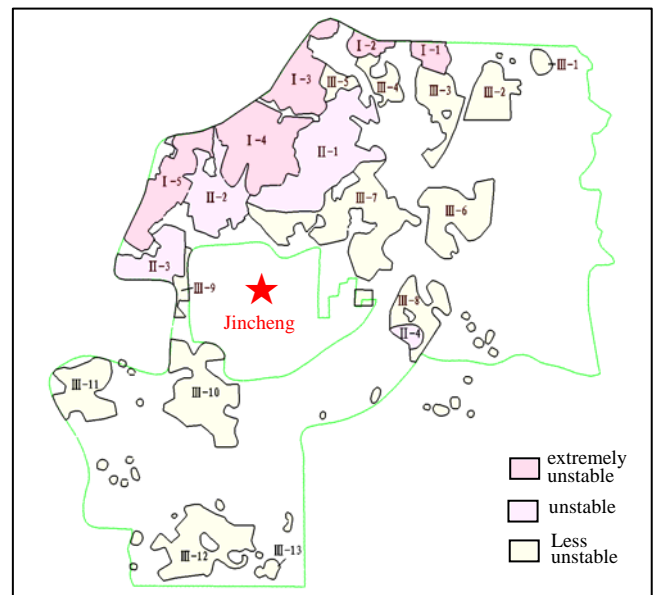

Figure 5. The stability appraisal map around Jincheng city

4. CONCLUSIONS

The survey and evaluation of stability of coalmine goaf areas around Jincheng city by remote sensing and GIS technology has reached the requirements of land planning department of Jincheng City and the results have been used in urban planning subsequently. However, due to the limitations of remote sensing technology and the complexity of the real world, coupled with dynamic changes of the distribution areas and thenumber of the goaves as coal exploitation continues, the results can not yet fully meet the requirements of urban architectural design at large scale, and geophysical or boring methods should also be used to determine the goaves and stability of foundation for constructions so as to provide the

necessary information for taking reasonable measures to carry out construction.

As a basic source of information, remote sensing has played an important role in extracting information of small coalmines that have disappeared. GIS, a tool for comprehensive analysis, has brought great convenience in evaluating the stability of goaves. Changes of ground elevation have close relation with coal mining, but a variety of human and natural factors can also cause changes of the ground surface, therefore, the reasons for the elevation change should be analyzed accordingly.

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