

# Risk assessment and remediation strategies for highway construction in abandoned coal mine region: lessons learned from Xuzhou, China

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Received: 31 March 2015 / Accepted: 28 May 2015 / Published online: 25 June 2015  
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**Abstract** The influence of abandoned mine subsidence on transportation facilities is a growing concern due to rapid urbanization and industrialization in China. Transportation infrastructures are being or will be developed in many areas with potential subsidence problems. Consequently, it is necessary to assess and mitigate the long-term and progressive residual subsidence effects on transportation facilities in such regions. This paper presents an integrated framework to identify and mitigate the risks of abandoned mine subsidence on highway infrastructures. The framework comprises four steps: comprehensive investigations of abandoned mine features; identification of subsidence mechanisms, conceptual model construction and risk assessment; optimization of remedial solutions and development of a management strategy. A case study that demonstrates a successful application of the framework is also presented in this paper. In this example, a technique that integrates remote-sensing analysis throughout surface features with conventional investigation methodologies is proved to be a potential tool to detect and understand areas that might be at risk of surface subsidence. Based on the analysis of the representative failure mechanisms observed in situ and the influencing factors, a methodology has been developed to assess the geohazards associated with mine subsidence. Moreover, the proposed criteria for stability classification allowed us to define three geohazard levels

on a regional scale. Subsequently, based on a brief review of remedial works made in China, the paper gives some recommendations to identify the most appropriate solutions to mitigate residual subsidence risk on transportation infrastructures. Such integrated decision-making framework will assist practitioners and regulators in identifying the potential risks of residual subsidence on transportation routes, optimising the most appropriate alignments, and assessing risk management practices.

**Keywords** Abandoned coal mine region · Highway · Integrated framework · Residual subsidence · Risk assessment · Remediation

## Introduction

The influence of abandoned mine subsidence on engineering structures is a growing concern of the coal industry in China and worldwide. The problem used to be precluded by avoiding previously mined regions, or preventing mining activity to take place. However, due to rapid urbanization and industrialization in China, these abandoned underground mine sites are currently being considered for major redevelopment and rehabilitation.

Many literatures indicate that subsidence resulting from mining is composed of three distinct phases: (1) initial, (2) active and (3) residual subsidence (Singh Madan 1992; He et al. 1994; Bell and de Bruyn 1999, 2006; Culshaw et al. 2000; Al Heib et al. 2005; Donnelly et al. 2007; Altun et al. 2010; among others). After the residual phase, the subsidence tends to stop and the surface is stabilised due to the establishment of an equilibrium between the overlying strata and abandoned mine workings. Changes in this natural–geotechnical-coupled system can cause damage to, or

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even failure of, the engineering structures. In a significant proportion of the documented cases, the geohazards caused by subsidence reactivation are due to human-induced hydrological changes and adjacent construction activities, and the deteriorative effect of groundwater on the previously stabilised strata is the primary mechanism of progressive subsidence and even collapse.

The design and construction of linear infrastructures, e.g., highways, high-speed railways and pipelines, are greatly influenced by post-mine environments, because the potential risks of various geohazards could lead to damage of engineering foundations, excessive maintenance, rehabilitation, re-routing and increasing costs.

Therefore, comprehensive assessment needs to be carried out to understand geo-mining conditions in the construction and adjacent areas. It is also necessary to analyse the interactive processes between the engineering foundations and the post-mine environments during the lifetime of the structures. Much research has been carried out since the 1970s to develop qualitative approaches to assess potential subsidence-related damage to transportation infrastructures in order to facilitate the selection of alignments in which risks are minimised (Healy and Head 1984; Sargand Shad and Hazen Glenn 1988; Jonce and Spencer 1977; Jones and O'Rourke 1988; Jones 2004; Hoffman et al. 1995; Tong et al. 2014; among others). However, such studies have seldom been applied to the construction of highways in China (Tong et al. 2004), where the decision-making is often based on sparse data collected and reported in unreviewed literature.

Based on rigorous analyses, this paper presents a methodological framework for risk assessment and zonation of abandoned coal mine regions for highway design, construction, and operation. The proposed approach has been applied to a 50-km-long section of Xuzhou highway in China.

## The transportation corridor northwest of Xuzhou, China and features of the associated abandoned coal mine

### Geology and historical mining activities

Xuzhou Coalfield is located in the northwest of the Yellow River floodplain. A summary of the geology is shown in Table 1. The geologic formation consists of three units: overburden quaternary deposits, a middle sandy mudstone unit and a lower coal bearing sandy mudstone unit. The upper unit generally consists of 40–130 m of medium to coarse sand and clay. The intermediate unit contains interbedded mudstone, sandstone and sandy mudstone, which are located directly over the mined coal unit. The lower

portion of the formation consists of gray to dark-gray mudstone, sandy mudstone, sandstone and limestone. Mineable coal seams within the study area occur in four zones in the lower formation, as shown in Table 1.

Highways, high-speed railways and pipelines use a natural northwest corridor that passes through 50 km<sup>2</sup> of an abandoned coal mine region (Fig. 1). The abandoned mines along the transportation corridor are illustrated in Fig. 1. Most mining activity in this area was conducted at depths between 90 and 600 m below ground, with a thickness between 7 and 8 m. The mining was generally performed with longwall methods and occasionally room-and-pillar methods, as shown in Table 2.

### Distribution of abandoned coal mines

Two potential highway alignments (Line A and B), traversing 50 km<sup>2</sup> of abandoned coal mine region, were proposed and are shown in Fig. 1. Line A and B both run through a couple of abandoned mines, including five major mines summarised in Table 2. The potential geohazards during the construction and operation of highway facilities and the associated mitigation costs should be considered as the controlling factors for final route selection.

The regional geological formations, geomorphologic units and mining features control the progressive residual subsidence. Any geological variation or human activities, such as lithology and major construction etc., can cause noticeable variations and transitions in the stability of the abandoned mines. Other features, such as active faults, outcrops, syncline, steeply inclined coal seam, and groundwater recharge, tend to occur in such areas, which could facilitate further development of residual subsidence.

Ground conditions have changed noticeably along the transportation corridor since the 2000s, and these changes adversely affect numerous engineering infrastructures. Particularly, sinkholes and differential settlement reduce the reliability and long-term stability of transportation infrastructures. The area affected by changes in post-mine conditions is generally wider than the construction areas of development.

### Methodology and results

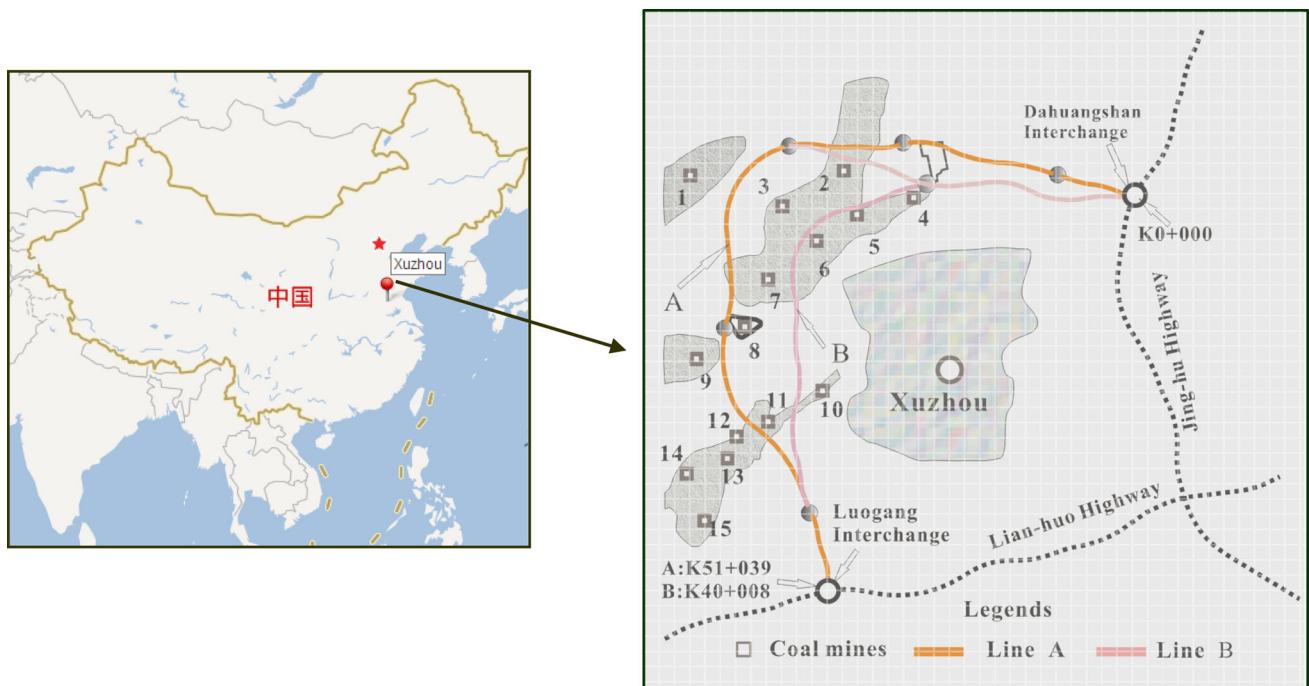
Although the hazards posed by the subsidence/collapse of old mine workings are well recognised, and many project-based methodologies have been presented in various literatures, there are no established risk management strategies to address the issue in China.

The prevention of subsidence hazards on transport routes such as highways or railways needs to be considered in the planning, construction and operation stages. In this

**Table 1** Generalised strata and mineable coal seams (Tong et al. 2006)

Units	Stratum symbol	Thickness (m)	Lithological character	Coal seam layers	Main mineable layers	Coal seam thickness (m)
Upper unit	Q <sub>4</sub>	40–130	Silty sand to sand, clay			
Middle unit	P <sub>2sh</sub>	>474	Mudstone, medium to pebbly sandstone			
Lower coal bearing unit	P <sub>2s</sub>	480–550	Mudstone, sandy mudstone, fine to medium sandstone, pebbly sandstone	3 thin coal seams	Discontinuous coal streak	
	P <sub>1x</sub>	180–220	Mudstone, fine to medium sandstone, pebbly sandstone	2–10 coal seams	2#, 3#	2#, 0.25–4.26; 3#, 0.3–1.8
	P <sub>1s</sub>	63–123	Mudstone, sandy mudstone, fine to medium sandstone	2–6 coal seams	6#, 7#, 8#, 9#	6#, 0.7–1.2; 7#, 0.76–4.94; 8#, 0.2–2.93; 9#, 0.21–5.92
	C <sub>3t</sub>	140–190	Limestone, mudstone, medium sandstone	10–12 coal seams	17#, 19#, 20#, 21#	17#, 0.14–0.49; 19#, 0.5–0.8; 20#, 0.29–1.56; 21#, 0.11–2.21
	C <sub>2b</sub>	19–50	Limestone, green-gray bauxitic mudstone			

Q<sub>4</sub> Quaternary, P<sub>2sh</sub> Upper Permian Shiqianfeng formation, P<sub>2s</sub> Upper Shihezi formation of Upper Permian, P<sub>1x</sub> Lower Shihezi formation of Lower Permian, P<sub>1s</sub> Lower Permian Shanxi formation, C<sub>3t</sub> Upper Carboniferous Taiyuan formation, C<sub>2b</sub> Lower Carboniferous Benxi formation



**Fig. 1** Schematic alignments of the NW highway and distribution of abandoned mines in Xuzhou, China

paper, an overall methodology for risk assessment and mitigation of abandoned coal mines under highways is illustrated in Fig. 2. Four steps need to be undertaken to identify areas affected by mining subsidence to predict the spatio-temporal distribution of future residual subsidence, and to locate critical points where significant subsidence is likely to occur and to optimise remedial solutions and operation management.

**Step 1: Integrated investigations of abandoned mines**

The subsidence-related geohazards on highway alignments should be taken into consideration in the initial stage of the project. A well-conceived selection of the alignment requires production of a detailed subsidence hazard map showing the “a priori” unstable areas. Therefore, an

**Table 2** Summary of mine features in Xuzhou Coalfield

Mine name	Mined coal seams	Mining thickness (m)	Depth of mine workings (m)	Mining depth-to-working thickness ratio	Strata dip (°)	Mine roof character		Mining methods	Roof controlling method	Time to stop mining
						Lithology	Axial compressive strength (Mpa)			
Liuxin	1#, 2#, 7#	1.27–2.94	1–2#, 120–260; 7#, 120–430	40–>300	15–80	Sandstone or mudstone	1–2#, 13–46.4; 7#, 50.8–86.4	Longwall	Fully caving	1996, partially 1982
Pangzhuang	1#, 2#, 7#, 8#, 9#	1–3.5	1–2#, 60–450; 7–9#, 70–430	45–300	<20	Mudstone or sandstone		Strike longwall	Fully caving	1977–1992, 1999–2003
Jiahe	2#, 7#, 9#	1.1–4.05	2#, 115–400; 7, 9#, 85–470	55–221	10–33	Mudstone or sandstone	37.55–146.5	Strike longwall	Fully caving	1972–1992
Xinhe	2#, 3#, 7#, 9#, 10#, 20#	0.85–10.3	2–3#, 50–140; 7–9#, 80–290; 10#, 290–310; 20#, 230–240	21–462	5–30	Sandstone or mudstone		Strike longwall	Fully caving	1962–1971; 1982–1986; 1990–2001
Dalu	7#, 9#	2.01–3.75	550	140–250	<25	Sandstone or mudstone	12.1–43.4	Longwall	Fully caving	1987–1991

integrated investigation of abandoned mines, consisting of field observations, geophysical surveys and remote sensing analysis, should be conducted.

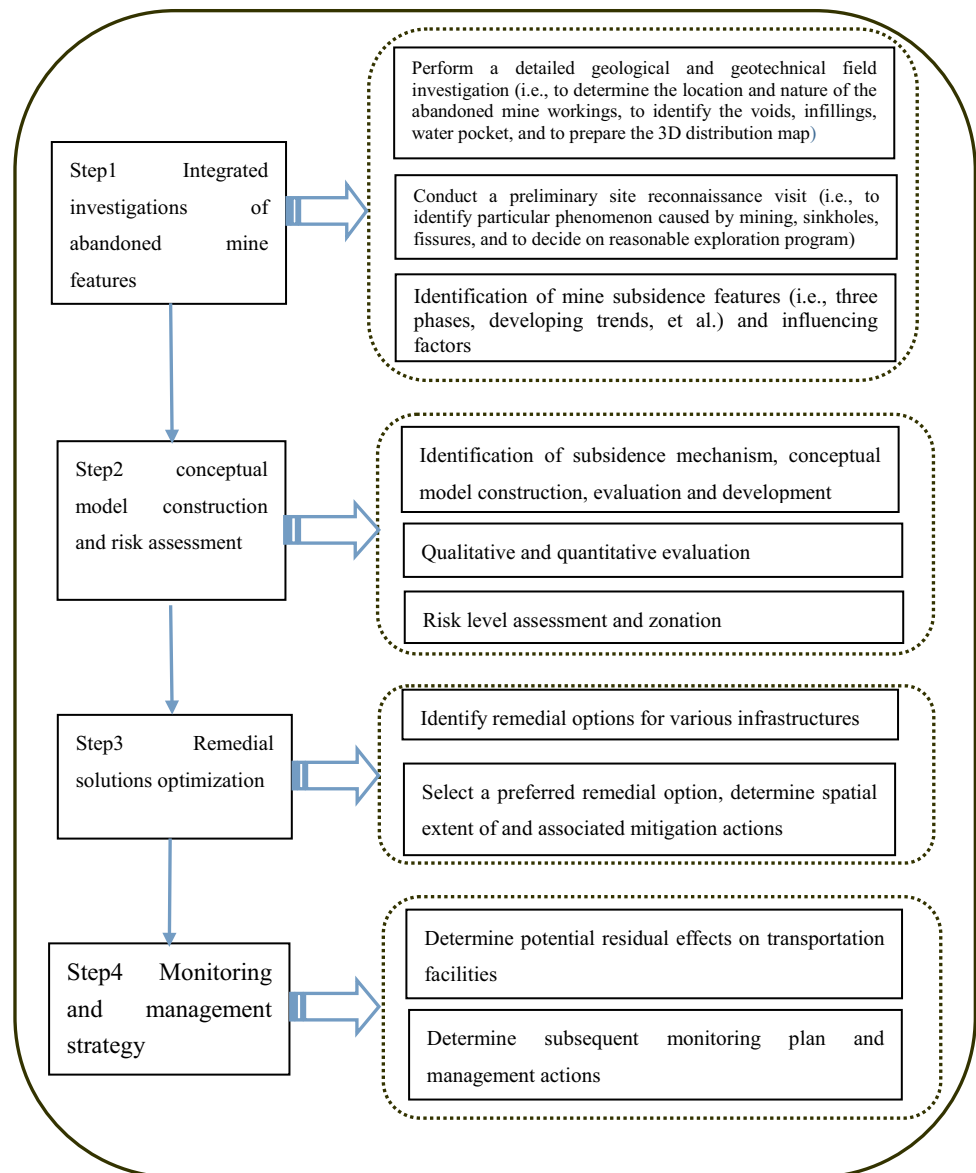
The first step of the investigation should focus on desk-studying the available information in order to produce a geo-referenced abandoned mine inventory as complete and representative as possible. This inventory includes detailed abandonment maps, geomorphological data, information on the chronology of sinkhole occurrence, and existing structural damage caused by subsidence and subsidence rates. Various geophysical techniques can be implemented to detect subsurface ground voids, including gravity and microgravity, cross-hole seismic tomography, resistivity, and ground-probing radar surveys. It should be noted that all geophysical anomalies require verification by drilling, but a thorough geophysical survey can reduce drilling costs significantly. A promising method is the integration of remote-sensing analysis throughout surface subsidence features with geophysical studies to detect subsurface voids.

The chronological remote-sensing images may reveal the most active areas and allow for assessment of variation trends. Thus, an estimate of the hazard can be expressed as the periodic expansion area. For sinkholes, this technique is particularly useful, because such discontinuous deformation is often quickly masked or obliterated by human activities. High-quality aerial photograph interpretation needs to be supplemented with a thorough field survey. Examination of the ground may help to pinpoint small subsidence features that are indistinguishable in the photographs. At this stage, interviewing local landowners to locate old and recent subsurface damage is useful, and this information can be a valuable complement to the mine subsidence map. It is important to bear in mind that it is very difficult to evaluate the potential hazard of those areas with no field observations.

For this particular project in Xuzhou, China, the database obtained from U.S. Landsat 5 and 7 included: (1) Thematic Mapper (TM) image data of 19 September 1987; (2) TM image data of 6 September 1994; and (3) Enhanced Thematic Mapper (ETM+) image data of 14 September 2000. The track number is 122/36. The spatial resolution of the visible and reflected IR band is 30 m, and that of the thermal IR band 6 is 120 m for TM and 60 m for ETM+.

Due to the lack of corresponding indications in the RS images, it is impossible to identify the subsidence area directly. However, surface water in the subsidence area is clear and easy to identify. The Modified Normalised Difference Water Index (MNDWI) threshold-based method (Xu 2006) was used to identify the mining subsidence-resulted surface water body. MNDWI is described as follows:

**Fig. 2** Framework showing methodological steps for abandoned coal mine risk assessment and remediation under transportation routes



$$\text{MNDWI} = (\text{Green} - \text{MIR}) / (\text{Green} + \text{MIR})$$

where Green is the reflectance value in the green visible band; and MIR is the reflectance value in the middle infrared band. As for the TM/ETM+ images, Green and MIR are band 2 and band 5, respectively. The water information could be extracted with an appropriate threshold value according to MNDWI. Compared with the NDWI threshold-based method (Mcfeeters 1996), the MNDWI image will result in more accurate extraction of open water features, as the built-up land, soil and vegetation are all negative values, and thus are notably suppressed and even removed (Xu 2006).

In this paper, the subarea covering the study sites was selected after image cropping and processed using Geomatica 8.2. Then the data was saved in the spatial

database of GIS and the spatial analysis and mapping were carried out using ARC/INFO NT7.2 and ARCVIEW 3.2.

Firstly, polygon vector graphics of the subsiding seep area obtained from RS images were imported into ARC/INFO software, and three space layers of the subsiding seep area at different times, 1987, 1994 and 2000, were formed. Then, the topological relations of these layers were analysed and the subsiding seep area was identified. Finally, the expanding trend of the subsiding seep area can be predicted by overlay analysis.

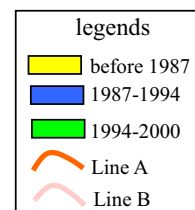
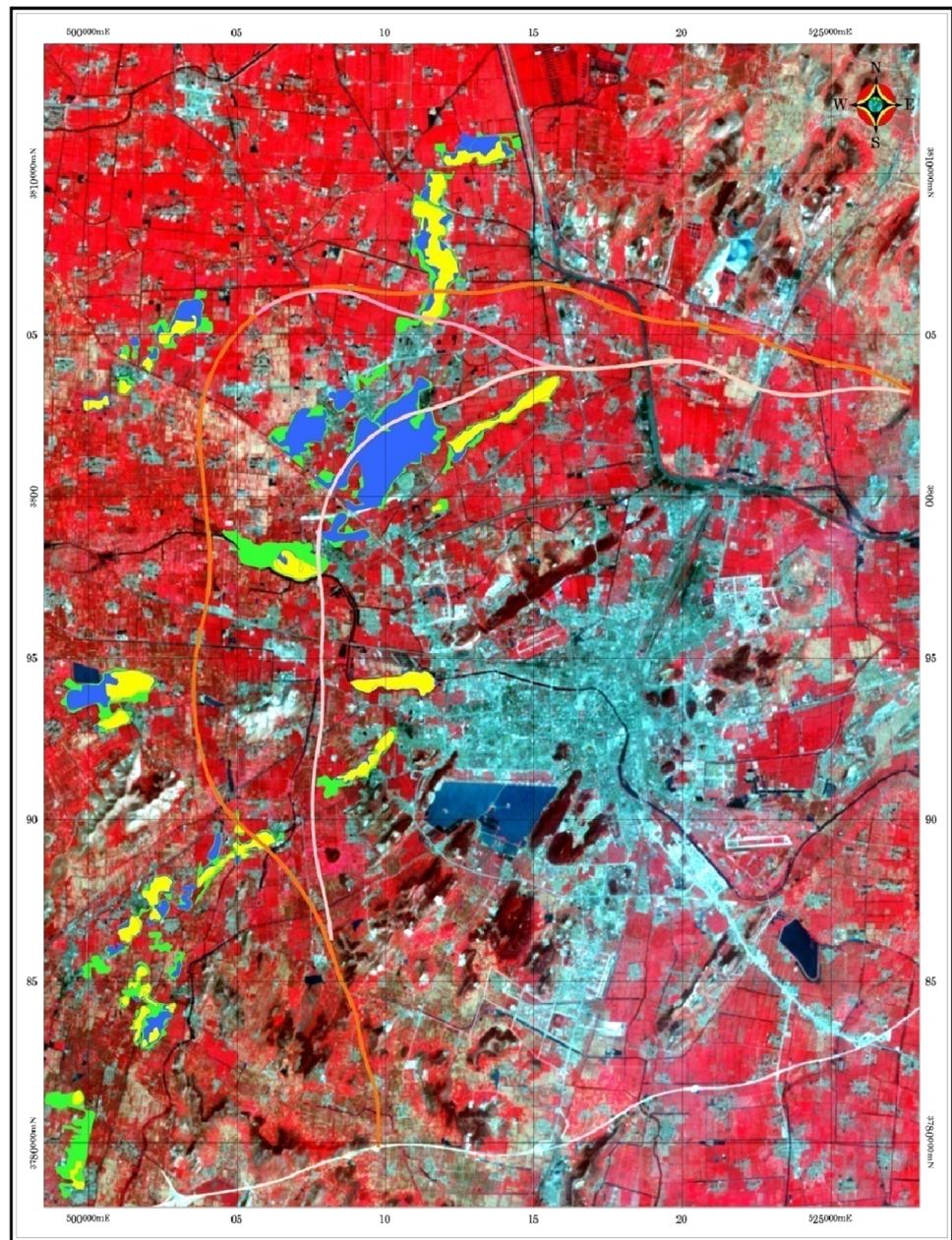
Of particular note is that the field investigation revealed that the water surface was 0.5–1.0 m lower than the ground surface. Moreover, some subsided sites may be masked or obliterated by human activities and natural processes. Thus, the identified subsidence area using this method is

smaller than the actually subsided area. Therefore, the concept of subsiding seeper area is used in the following context in this paper, as distinguished from the concept of the subsidence area.

Figure 3 shows the distribution of the identified subsiding seeper area along the alignments at different

stages. Table 3 gives the areal data of different mines chronologically. It can be observed that the subsiding seeper area increases from 12,032,635 to 63,233,514 m<sup>2</sup> between 1987 and 2000, which is about 400,0000 m<sup>2</sup> per year towards the Northwest. This estimate agreed with the field survey, and could be attributed to the

**Fig. 3** Identification of expansion of the subsiding area at different times along the proposed alignments



**Table 3** Comparison of subsiding seep area at different times

Mines	Subsiding seep area (m <sup>2</sup> )			Expansion area (m <sup>2</sup> )	
	September 1987	September 1994	September 2000	87 → 94	94 → 2000
Liuxin	3,182,827	5,120,030	6,564,887	1,937,203	1,444,857
Jiahe	727,972	856,311	2,731,508	128,339	1,875,197
Pangzhuang	1,347,747	10,208,969	13,518,279	8,861,222	3,309,310
Xinhe	2,464,654	5,120,030	6,956,681	2,655,375	1,836,651
Daliu	1,786,503	2,003,931	25,496,550	217,428	23,492,619
Others	2,522,931	4,350,491	7,965,610	1,827,560	3,615,119
Total	12,032,635	27,659,762	63,233,514	15,627,127	35,573,753

distribution of coal mines around Xuzhou City and their mining directions.

Once the alignment of the highway has been selected, a thorough exploration program is commonly conducted in order to detect residual voids and highly hazardous areas, especially in sections where unstable conditions have been identified. This investigation generally includes drilling programs and geophysical surveys. Along the selected alignment A, georadar, microgravimetry and electric resistivity tomography surveys were performed.

## Step 2: Risk assessment

To address abandoned mine risks and develop an effective long-term hazard management strategy, a thorough process-based understanding of abandoned mine subsidence mechanisms should be sought. It was recognised that surface movements due to underground coal mining activities have three phases: initial, active and residual subsidence. Active subsidence refers to all surface movements that occur simultaneously with the mining operations, while residual subsidence is that part of the surface deformation that occurs after the cessation of mining. Residual

subsidence is the foremost concern over abandoned mine lands. The duration of residual subsidence is of particular importance from the standpoint of damage to the surface structures built after the mine has been abandoned. Time spans during which surface subsidence may occur vary markedly with the mining method being utilised. The subsidence mechanisms above abandoned mines are summarised in Table 4. In order to identify the possible mechanisms, an initial desk study on the local geology, hydrogeology and mine history should be carried out.

Furthermore, preliminary conceptual models incorporating the processes driving the mechanisms listed in Table 4 may be constructed (Fig. 4). After that, continued monitoring data of ground subsidence should be constantly collected to evaluate and develop the first conceptual models into general models. Subsequently, the controlling parameters for these models should be identified, especially those related to abandoned mine workings, which may include one or more of the factors shown in Table 4. For transportation routes, the surface topography and the layout of local highways and infrastructures were also included in the model, as were the surveyed locations and sizes of known sinkhole locations. Generally, these models focused

**Table 4** Mechanisms of surface subsidence above abandoned mine [Modified from Singh Madan (1992)]

Method of working	Residual subsidence mechanisms	Time effects (residual subsidence duration)	Key influencing factors
Partial extraction methods, e.g., room and pillar mining	Collapse of roof beds spanning adjacent pillars; pillar failures (spalls, squeezes or crushes); pillar punches into weak roof or floor; pillar soften or weakened by weathering	Major occurrence of surface subsidence may be delayed for decades, and up to 50–100 years, often sudden and unpredictable	Depth of working, mine geometry, strength and deformation characteristics of the roof floor and pillar, types of roof control, character of the overburden, extent of fracturing, presence of old mined-out workings, presence of water, non-mining factors
Total extraction methods, e.g., longwall mining	Gradual compaction of the subsided ground; collapse of residual voids; creep and natural compaction of broken rockmass under the overburden load; engineering induced ground settlement and the possible reactivation of faults, etc.	Relatively short, typically varying between a few weeks and about 10 years; the magnitude of residual subsidence rarely exceeds about 10 % of the total subsidence	Nature of overburden, ratio of mining depth and working thickness

on the highway corridor with 500 m on each side, and could be used as a reference for planning the necessary investigations.

The performance-based criteria prescribed by the Transportation Ministry of China required that the upgrade highway works should be designed for: (a) a 100-year design life, and (b) a designated speed limit of 120 km/h, meaning there should be no acute change longitudinally or laterally.

The risks posed by the various conceptual models (Fig. 4) over the 100-year design life include the possibility of: (a) a sinkhole type collapse, where there is a relatively shallow depth of roof cover; and (b) a small or large-scale trough subsidence with deeper overburden.

Both scenarios are likely to pose significant hazards to the vehicles travelling at the designated speed. Another effect of mine collapse is the possible failure of nearby structures, such as bridges and retaining walls. These risks would need to be addressed.

The models discussed above provide the data necessary for the further assessment and analyses. A comprehensive assessment of risk levels in different sections along the alignments can be conducted as follows.

### Qualitative evaluation

A qualitative analysis approach was used to assess possible instability conditions, so that all potentially hazardous zones could be readily defined for a detailed deterministic assessment. For this initial quick approach, the following important factors affecting mine subsidence are selected: (a) the attitude of the stratum, (b) the geological structure, (c) the ratio of the mining depth and the working thickness ( $H/m$ ), (d) mining methods, (e) mining time, and (f) dip of the seam. Depending on the geologic and mining conditions in Xuzhou Coalfield, the engineering geological stability may be evaluated firstly using the criteria and summarised in Table 5.

### Quantitative assessment

This analysis was carried out by essentially employing three parallel analytical approaches: (1) using empirical methods (Singh Madan 1992), such as the graphical method, profile functions and influence functions; (2) utilising the simplified structural analysis method, such as the pressure-arch theory (Bieniawski 1984); and (3) using numerical simulation methods.

In this study, an assessment of ground movement due to abandoned longwall mines was conducted utilising the Mining Subsidence Prediction System (MSPS) developed by the University of Mining Sciences in Xuzhou, China. MSPS uses the stochastic probability integral method as a

**Fig. 4** Representative forms of ground movement associated with coal mine workings (not to scale). For longwall mining, **a** gradual compaction of subsided ground; **b** collapse of residual voids. For room-and-pillar mining: **c** a stable room and pillar workings, **d** unstable room and pillar workings due to weak mine roof, **e** unstable room and pillar workings due to pillar failure (modified from Gray Richard 1988; Helm et al. 2013; Swift 2014)

basis for the calculation of subsidence associated with underground mining. The basic principle of the method is to apply the law of superposition to determine the overall influence of an extraction area.

Based on the predicted residual subsidence, the stability zones along the alignments can be grouped according to the criteria presented in Table 6. In addition, the acceptable ground deformation for the various types of highway structures over abandoned mines is given in Table 7, according to the experiences of the highway construction in China.

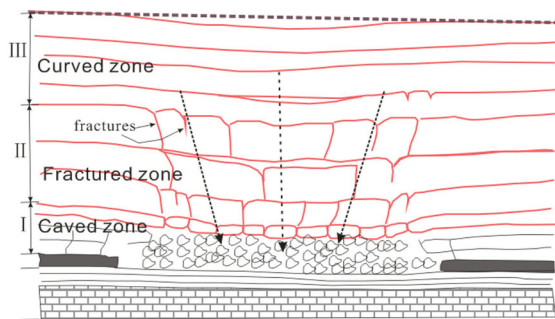
### Comprehensive evaluation and risk classification

It should be pointed out that several special conditions should be considered in the stability assessment: (1) the unique geological and mining conditions, e.g., faults and steep seam mining; and (2) the requirements of nearby structures, e.g., long tunnels and large-span bridges, and retaining walls. These conditions will be considered as potentially unstable circumstances and need special study.

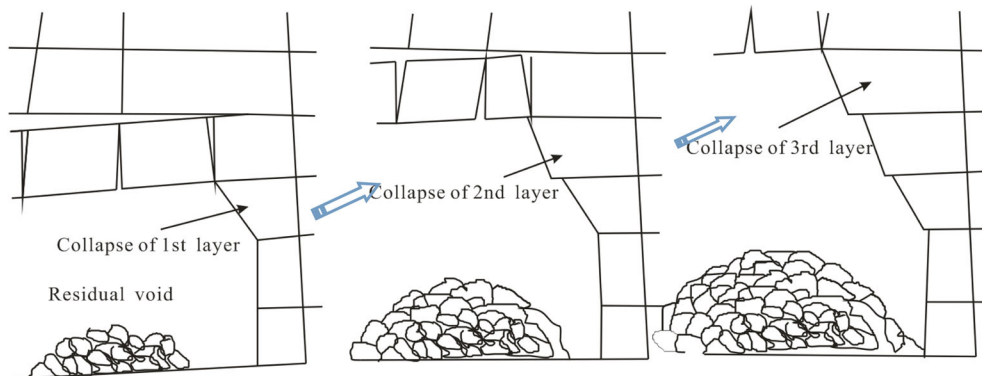
The comprehensive evaluation of subsidence damage to highway structures should stem from the following principles: If any unstable condition is identified based on Tables 5 and/or 6, the stability classification is unstable. The condition can be considered as stable only if all the requirements presented in Tables 5 and 6 are fulfilled.

Based on the above qualitative and quantitative evaluation methods, the risk classification analyses for Pangzhuang Mine were carried out. From K16 + 500 to K22 + 000, the 1#, 2#, 7#, 8# and 9# coal seams underlie alignment B (Fig. 5). Most mine activities ceased in the 1980s. However, part of the abandoned coalfield is still operating. For example, numerous faces of coal seam 7# were mined during 2002–2005. The predicted residual subsidence along the alignment from 2002 is shown in Fig. 6, and different colors represent different stable sections. The figure shows that the maximum vertical subsidence from 2002 was 1167.5 mm. This indicates that the corresponding section from K20 + 220 to K21 + 200 should be treated during highway construction. Therefore, these sections have been classified into the unstable type (III). The evaluation of other sections is given in Table 8 and Fig. 7, based on the geological and mining conditions.

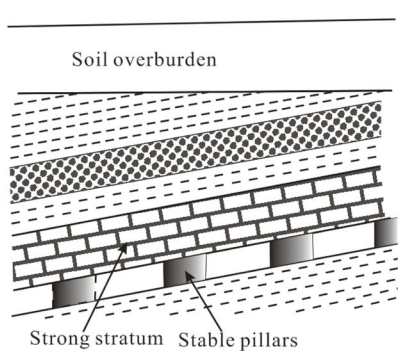




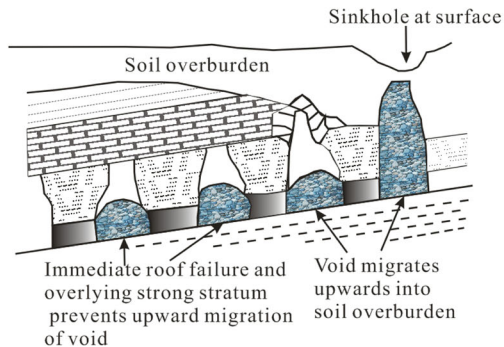
(a) Gradual compaction of subsided ground



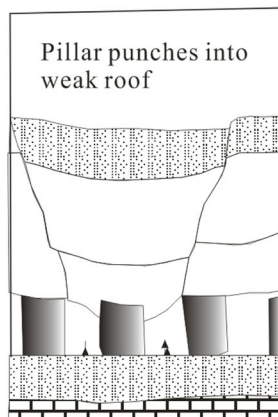
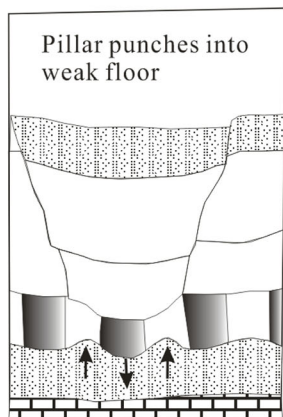
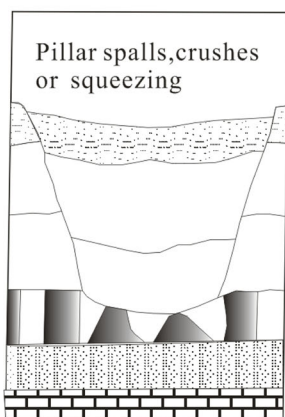
(b) Progressive failure leading to void stabilization by arching or the void will reach surface



(c)



(d)



(e)

**Table 5** Criteria for the assessment of engineering geological stability of abandoned mines

Stable classification	Mining conditions	Geologic conditions	Mining effects
Stable (I)	$H/m > 30$ ; longwall caving method; more than 5 years after the cessation of mining	Level coal seam ( $\alpha < 25^\circ$ ); no large geological structures	Surface movement is small and continuous
Basically stable (II)	$H/m > 30$ ; longwall caving method; 2–5 years after the cessation of mining	Inclined coal seam ( $25\text{--}55^\circ$ ); no large geological structures	Surface movement is relatively large and continuous
Unstable (III)	$H/m < 30$ ; shallow pillar-and-room method or strip pillar method; less than 2 years after the cessation of mining; active mining or future mining	steeply inclined coal seam ( $>55^\circ$ ); having faults or folds; shallow seam outcrop; complicated hydrogeological conditions	Surface movement is very large, and discontinuous damage occurs, such as sinkholes, faulting and shearing, etc.

$H/m$  mining depth-to-working thickness ratio

**Table 6** Stability assessment criteria with reference to surface residual deformations over abandoned longwall mines

Stable classification	Surface residual deformations			
	Vertical subsidence $W$ (mm)	Tilt $I$ (mm/m)	Horizontal strain $\varepsilon$ (mm/m)	Curvature $K$ (mm/m <sup>2</sup> )
Stable (I)	$\leq 200$	$\leq 3$	$\leq 2$	$\leq 0.2$
Basically stable (II)	200–300	3–6	2–4	2–4
Unstable (III)	$\geq 300$	$\geq 6$	$\geq 4$	$\geq 4$

**Table 7** Acceptable ground deformations for highway structures in abandoned mine areas in China (Tong et al. 2006)

Structure types	Allowable ground deformations		
	Tilt (mm/m)	Horizontal strain (mm/m)	Curvature (mm/m <sup>2</sup> )
Subgrade	4	3	0.3
Bridges			
Freely supported	3	2	0.2
Non-freely-supported	2	1	0.15
Tunnels	3	2	0.2
Brick-concrete buildings	3	2	0.2

Tables 9 and 10 summarise the evaluation results of the proposed highway alignments, and the potential risks on various transportation infrastructures, including embankments, bridges, service structures and utility corridors. Based on this comprehensive comparison, Line A was considered to be a better option, because the potential geohazard associated with abandoned mines is relatively low.

### Step 3: Optimization of remedial solutions

Geohazard mitigation along the transportation routes requires the identification of the areas affected by subsidence (especially sinkholes), the prediction of the spatio-temporal distribution of future subsidence, and location of the critical points/sections where sinkholes are likely to occur. This information is commonly derived from the analysis of Step 1 and Step 2. In practice, the highway sections underlain by existing or potential sinkholes should be treated seriously.

Numerous techniques have been developed in the attempt to solve the problem of surface subsidence above the abandoned and mining areas (Okonkwo et al. 1988; Gourc et al. 1999a, b; among others). However, as highways normally cover a broad geographical area, there are quite often substantial variations in topography and ground conditions along the route. To a large extent, residual subsidence over abandoned mines is governed by various factors, such as structure types, local geology, mining conditions, and mining methodology. It is important to consider the features of highway structures, such as embankments, bridges, and culverts, etc., against the effects of mine subsidence.

Several mitigation strategies can be applied to avoid or reduce subsidence/sinkhole-related damage on transportation infrastructures built upon abandoned mine areas. (1) Prevent the geohazards by selecting a route that avoids the sinkholes and subsidence-prone zones; (2) Minimise the geohazards associated with the processes in which the

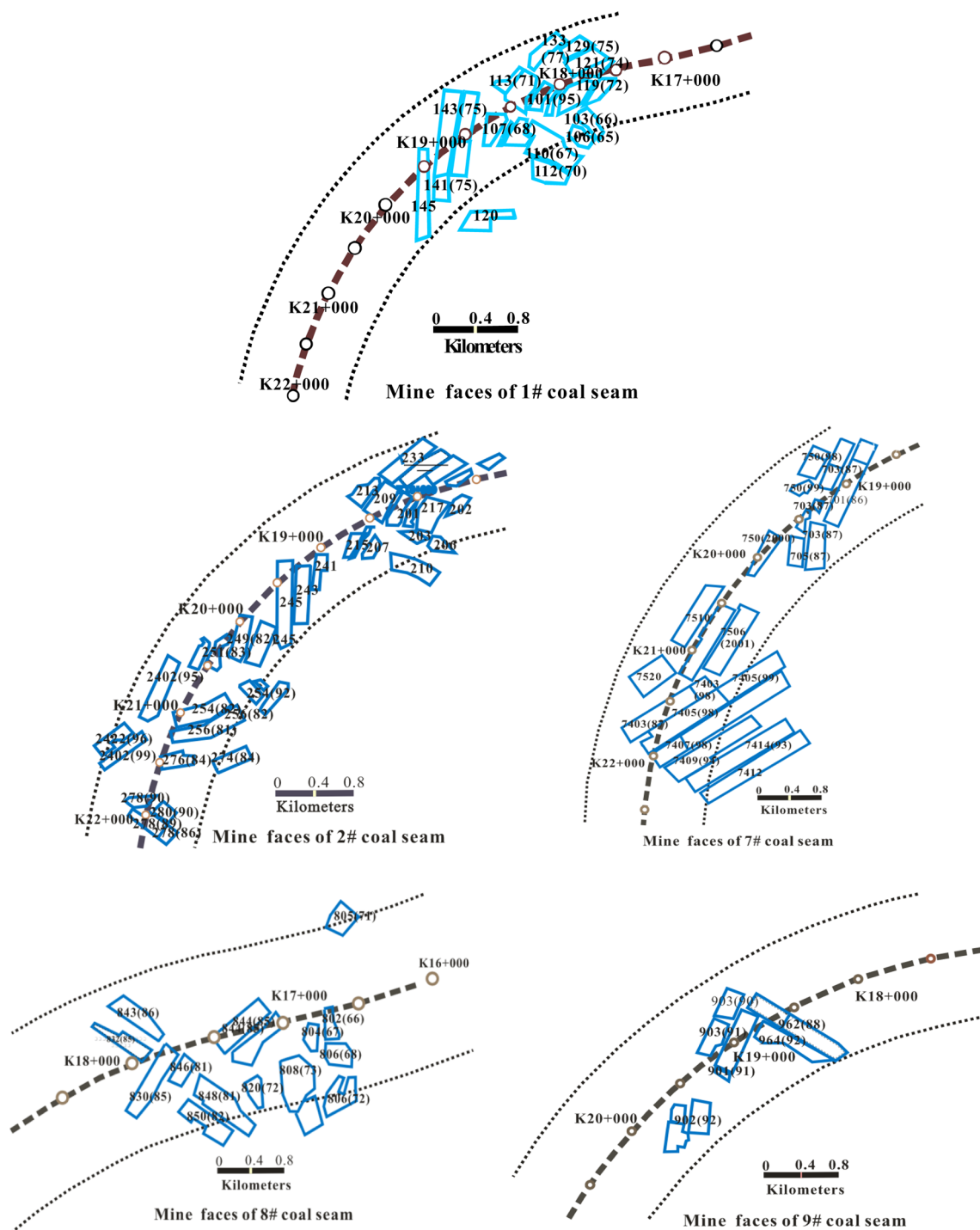
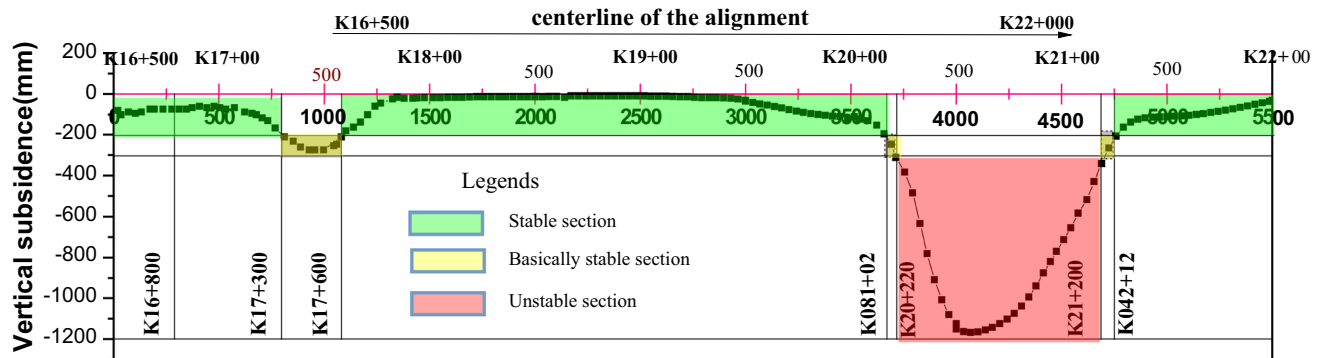


Fig. 5 Distribution of labeled mine faces of #1, 2, 7, 8, 9 coal seam

subsidence/sinkhole would develop (e.g., re-mining and underground water pumping). Generally, this strategy is highly uncertain and not effective enough due to the hidden features of the processes behind the subsidence phenomenon. (3) Reduce vulnerability of the structure through the incorporation of subsidence/sinkhole-resistant designs.

Table 11 summarises the engineering solutions to mitigate mining subsidence/sinkhole damage on highways according to classification of risk level. Geohazard mitigation for critical and spatially restricted structures like bridges or buildings is generally conducted by means of special foundations (e.g., rafts/bridging solutions), whose selection



**Fig. 6** The predicted subsidence from 2002 along the alignment in Pangzhuang mine

and design are based on thorough site investigations that include geological-geomorphological mapping, geophysical surveys and boreholes. However, this strategy is not cost-effective in projects involving the construction of highways in subsidence-prone areas over long distances. A common practice in abandoned mine areas is to fill the residual voids and fissured rock mass (e.g., grouting). In areas where the thickness of the overburden is too high, another widely applied measure is the installation of high-resistance geosynthetics at the base of the embankment. It is a simple and economic alternative to increase the bearing capacity of the soil and span the subsidence/sinkhole-prone areas.

It is quite often that the risk is disregarded or overestimated due to the lack of sufficient data on the spatial and temporal probability of geohazards associated with subsidence/sinkholes in the areas where roads are built, leading in the latter case to an excessive investment in mitigation. Therefore, numerical analysis was often used to optimise mitigation solutions, to ensure the safety of motorists in the event of mine subsidence (Helm et al. 2013).

China has constructed more than 20 highway projects in abandoned coal mine regions that have been affected by the residual mine subsidence. The general information of these case histories, the characteristics of abandoned mines, the investigation methods, and the remedial actions are shown in Table 12.

A common mitigation measure in abandoned mine areas in China is to improve and strengthen the ground by grouting (as shown in Table 12). Various grouting techniques have been applied to stabilise the existing structures and new construction over abandoned coal mines. All these techniques can fall into two categories: flushing and grout columns (Andromalos and Ryan 1988). With the flushing method, the entire mine in the affected area is filled, while the grout columns are utilised to shorten the free span of a mine roof to prevent void migration. Details of these two methods and their relative technical and economic advantages are presented in various literatures (Okonkwo et al. 1988).

A Risk-free mitigation strategy may involve extensive application of costly treatment, and it is normally not the most cost-effective solution. In order to develop the best strategy, a cost-benefit analysis based on risk assessments of “with mitigation” and “without mitigation” scenarios should be considered to evaluate the expenditures and to optimise resources.

This study proposes subsidence/sinkhole susceptibility zonation to address this issue. The susceptibility appraisal helps to identify the sections and particular points in which the application of investigation programs and corrective measures would have a better cost/benefit ratio.

The following analysis on Pangzhuang Mine is an example of the mitigation design (Fig. 8). Unstable sections over abandoned longwall mines should be treated conservatively by using the flush grouting method. Especially, areas passing through and adjacent to the steeply inclined coal seam outcrop may be considered as key points, where the residual voids may induce sinkholes, fissures and other discontinuous deformation. For the basically stable sections, highways can be reinforced by incorporation of tensile membranes or geogrids in the sub-base and embankment. This structure allows the road to bend, but does not allow a catastrophic collapse. Typically, three layers of geotextiles or grids were placed in the sub-base and embankment in the studied project.

#### Step 4: Monitoring and management strategy

The objective of the monitoring was to measure potential movements of the ground and establish a baseline level of stability. The scale of monitoring depends on the identified risk levels. Minor monitoring was utilised in the low-risk sites, while the highest risk sites should be monitored comprehensively during the planning, construction and operation phases. Each phase has specific monitoring requirements and techniques, which may include visual and surveyed surface methods, and various inhole methods,

**Table 8** Evaluation results of Pangzhuang mine along the alignment

Sections	Mined coal seam	Mining thickness (m)	Mining depth (m)	Strata dip (°)	Mining depth -to-working thickness ratio	Time to stop mining (year)	Classification
K16 + 500-K16 + 800	Oxidised zone (7, 8, 9#)			>25			II
K16 + 800-K17 + 300	2, 8	1.4-1.9	70-144	<25	61-110	1982-1985	I
K17 + 300-K17 + 600	1, 2, 8, 9	1.4-3	90-220	12-20	48-110	1982-1988	II
K17 + 600-K20 + 180	1, 2, 7, 8, 9	0.19-3.5	60-430	10-15	45-430	1977-2003	I
K20 + 180-K20 + 220	2	1.55-2	310-370	12	170-239	1992	II
K21 + 200-K21 + 240	2	1.5-2	390-450	12	200-300	1999	II
K21 + 240-K22 + 000	2	1.5-2	370-450	12	200-300	1999	I

e.g., inclinometers, time domain reflectometry (TDR) cables and multipoint borehole extensometers.

Although it can be costly to treat high-risk sites, the long-term benefit may be substantially influenced by adjacent construction activities after the operation of transportation infrastructures. A management strategy needs to be developed based on an understanding of the controlling parameters, because the consequences of long-term damage may be severe. The protective zone should be established on both sides of highway sections with high subsidence/sinkhole risks. Within these zones, construction activities (e.g., re-mining, underground water withdrawal, deep excavation) are restricted or prohibited.

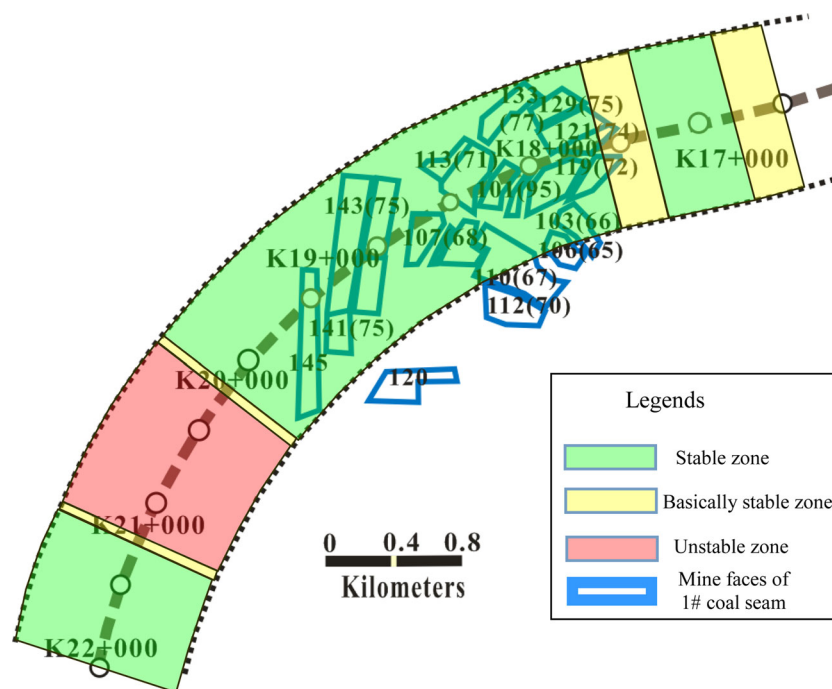
### Discussion and conclusions

Abandoned mine workings may pose a serious threat to transportation infrastructures, as significant settlement or sinkhole can result in disastrous consequences. Consequently, the construction of highways in abandoned mine regions should be accompanied by a comprehensive subsidence mitigation strategy and a more holistic decision-making framework should be developed. This paper presents an integrated methodology to address this issue. The approach has been applied to a highway that was built in an area with numerous abandoned mines. With some modifications, this approach could also be applied to other linear infrastructures (e.g., railways, pipelines). The key contents of this methodology can be summarised as follows:

(1) Integrated investigation of abandoned mine features and development of a comprehensive database for risk assessment. The integration of the traditional investigating methods (e.g., geophysical techniques, drillings) with satellite remote sensing proved to be a successful and promising tool in characterising mine subsidence features. Thorough geophysical surveys (e.g. electrical resistivity methods) have the capacity to show strata structure associated with subsidence/sinkholes. Besides, the comparison of aerial imagery at different phases may reveal paleo-subsidence or sinkholes masked or obliterated by human activities and natural processes, recognise the most active zones and assess the tendency of subsidence development and sinkhole generation. The proposed subsidence/sinkhole susceptibility zonation may serve as the basis for further investigations and for the selection of the mitigation measures.

Since the feasibility of alignment decision-making is only as strong as the underlying data, it is imperative that background information should be gathered and weighed in the decision-making process. A major problem with abandoned mines is the lack of knowledge regarding the extent of the problem, and it is difficult to predict when and

**Fig. 7** Proposed risk level zonation for the analysed stretch of highway superimposed on a simplified mining profile (Pangzhuang mine taken as an example)



where it will occur. For this case study, sufficient geological and mining data along the proposed alignments in Xuzhou Coalfield are available. However, for other cases, it may be difficult to proceed with the assessment, owing to the limited data from mining authorities. In such circumstances, information from other resources may be highly useful. For instance, environmental agencies as well as large regional mine operators may possess a huge knowledge base that can be used to identify the potential risks to highways.

(2) Identification of causal mechanisms, conceptual model construction and risk assessment. The evaluation of instability processes of residual subsidence/sinkholes is generally dependant upon internal factors, such as the low mechanical strength of disturbed rocks, or external natural or human factors. Based on experience from China and worldwide, most of the failure or instability mechanisms observed in abandoned mine environments fall into two groups: failures associated with the abandoned longwall workings and failures associated with the abandoned room-and-pillar workings. Accordingly, two types of subsidence features are recognised above abandoned mines: sinkholes and troughs. In terms of the influence of residual subsidence on the highway structures, engineers are more concerned by sinkholes because of their sudden and unpredictable features, which may happen up to decades after mining activities. Furthermore, the construction and

evaluation of conceptual failure models related to main subsidence mechanisms may serve as the basis for further risk assessment. The outcome will help to identify where large depressions or sinkholes may occur.

Based on qualitative and quantitative evaluations, three stable zones with different risk levels can be identified: stable, basically stable and unstable zones. In this process, an engineering geological method based on the investigation of geological and mining conditions, traditional analytic methods combining theory and experience, and numerical simulation methods have both advantages and disadvantages, and can be used at different stages of highway construction. Generally, the engineering geological method is adopted at the initial phase of the feasibility study when an experienced engineering geologist is needed. The traditional analytic methods are applicable to the preliminary design phase, and must be reevaluated to account for the site-specific geological and mining conditions and the residual subsidence features based on monitoring data. Finally, the numerical simulation methods are utilised in the construction design stage. The large subsidence/sinkhole susceptibility sections and particular points would be of special concern, and a numerical modeling approach is useful for simulating the progressive caving or compacting of disturbed strata, as well as assessing the performance of a remedial method in given geo-mining and strata conditions.

**Table 9** Summary of the risk assessment results for the proposed highway alignments based on a combination of qualitative and quantitative analyses

Stability zones	Sections		Potential impacts				Risk level
	A-line	B-line	Embankments	Bridges	Service structures	Utility corridors	
Stable	Liuxin mine: 840 m, K16 + 510–K17 + 350, Xinhe mine: 650 m, K39 + 700–K40 + 300, K40 + 850–K40 + 900 Daliu mine: K32 + 900–K33 + 900, 1000 m	Pangzhuang mine: 3840 m, K16 + 800–K17 + 300, K17 + 600–K20 + 180, K21 + 240–K22 + 000; Jiahe mine: 1000 m, K22 + 000–K23 + 000; Xinhe mine: 325 m, K30 + 675–K31 + 000	Minor to negligible cracking, sagging, minor repairs required	Minor cracking, opening and closing of construction joints in abutments, cracking and spalling of concrete decks	Minor to negligible settlements, undetectable foundation movements	Minor to negligible stressing of service lines, unlikely disruption of service	Negligible to very low
Basically stable	Liuxin mine: 100 m, K16 + 060–K16 + 110, K16 + 460–K16 + 510 Xinhe mine: 100 m, K40 + 300–K40–350, K40 + 800–K40 + 850	Pangzhuang mine: 680 m, K16 + 500–K16 + 800, K17 + 300–K17 + 600, K20 + 180–K20 + 220, K21 + 200–K21 + 240 Jiahe mine: 700 m, K23 + 000–K23 + 700; Xinhe mine: 100 m, K31 + 000–K31 + 50, K31 + 300–K31 + 350	Undulations, Tension cracking, slightly settlement, pavement potholing, unlikely disruption of road use	Superstructure distress, horizontal displacement, bearing damage or damage to abutments, warping, or tilt of bridge decks, bumps at compressed and open expansion joints	Medium settlements, tension cracking, foundation movements,.	Stressing service lines, sagging, possible disruption of services	Moderate–considerable
Unstable	Liuxin mine: 350 m, K16 + 110–K16 + 460 Xinhe mine: 450 m, K40 + 350–K40 + 800	Pangzhuang mine: 980 m, K20 + 220–K21 + 200 Jiahe mine: 0 m; Xinhe mine: 250 m, K31 + 050–K31 + 300	Adverse effects on driving dynamics, large-scale cracking affecting base/subgrade, sinkholes, road surface potholing, high settlements, severe local gradients, likely disruption of road use, safety hazard	Instability of primary structural members, possibility of collapse	Major differential movements, foundation structural collapse, potential safety hazard	Severing of utilities, lines, over-tensioning of cables, likely disruption of service, safety hazard	High to very high

**Table 10** Summary of stability zones along the alignments

Alignments	Total length (m)	Length of stable zone (m)	Length of basically stable zone (m)	Length of unstable zone(m)	Length of subsiding seep area(m)	Subsiding seep area (m <sup>2</sup> )	Estimated remediation cost (× 10 <sup>4</sup> yuan)
A	2490	1490	200	800	1397	1,444,944	12,698
B	7875	5065	1480	1230	5184	4,620,795	32,569

Subsiding seep area indicates the area within transverse range of 500 m on each side of the highway

The remediation cost indicates the treating cost using the general grouting method

**Table 11** Matrix for assessing optimum remedial options for stabilising identified geohazards associated with highway embankment

Risk level	Rafts/Bridging solutions		Filling schemes			Reinforced soil		Hybrid solution
	Simple supported/continuous raft	Piled raft/deep beam	Flush grouting	Grout columns	Artificial rock strata	Basal reinforced embankment/geosynthetic solution	Piled embankment	Grouting + reinforced soil
Negligible to very low	×	×	×	×	×	(●)	×	×
Moderate–considerable	(●)	(●)	(●)	●	●	●	(●)	(●)
High to very high	●	●	●	(●)	(●)	(●)	●	●

× inapplicable, (●) applicable to a certain extent, ● applicable

(3) Optimization of remedial solutions. Over the years, numerous techniques have been developed in attempts to solve the problem of subsidence in abandoned and active mine areas (illustrated in Table 11). In this case study, the flushing grouting method using the large-volume flyash-cement grout mixtures was utilised to treat unstable zones, whereas the reinforcement method using tensile membranes or geogrids in the sub-base and embankment was applied to basically stable zones.

However, due to the complicated networks of underground tunnels and mining system, as well as variation of the regional geology and mining conditions, many of the engineering solutions may be not appropriate. For example, grouting is commonly used to fill residual voids and stabilise the overburden disturbed and fissured strata. If there is high groundwater movement, the difficulties of sealing the treated area make grouting ineffective. The volume of grouting mixtures and the fluid direction may be not easily controlled. The alternative way is to look for the obvious problems, such as known sinkholes, avoid them and build

strength and safety measures into the infrastructures. In some problematic sections or points, e.g., faults and outcrop of steep seam mining, additional safety measures should be used after the cavities have been grouted.

(4) Development of a management strategy. In practice, highway contractors and inspectors may not have expertise in managing highway construction in the abandoned mines. And most deformations criteria developed for industrial and civil engineering structures are not applicable for transportation facilities such as embankments, bridges, and culverts. Thus, field observations of highway structures may reveal the principal features associated with abandoned mine damages, and contribute to the establishment of correlated criteria.

Finally, it must be pointed out that socioeconomic factors should also be incorporated into the evaluation and establishment of a highway alignment. Based on the identification and thorough understanding of site conditions, realistic estimates of the costs should be identified and weighed prior to the selection of a



**Table 12** Summary of case histories of abandoned coal mine treating projects under highways in China (Tong et al. 2006)

Case no.	Projects	Main characteristics of abandoned mines										
		Mining depth (m)	Mining thickness (m)	Mining depth-to-working thickness ratio	Mining layers	Mining method	Mining time	Extraction ratio (%)	Roof management way	Back filling condition of mine workings	Filling condition of residual voids	Collapse condition of mine workings
1	Jing-fu highway, east ring of Xuzhou, Jiangsu	25–98	1–2	25–49	5	Longwall	1995–1998	80	Natural collapse	16–19#, filling	Water filling	16–19# collapse, 20 not collapse
2	Dan-la national highway, section of Machangyuan-gaomiao, Qinghai	0–120	1.5–2.5	0–48	1	Longwall	In ancient times and the 1980s	30–50	Natural collapse	10 % filling ratio	Unfilled	Partially collapse
3	Tai-lai, Tai-xin highway, Taian, Shandong	428–600	1.86–2.3	200–260	1	Longwall	1997–1999	80	Natural collapse	Unfilled	Unfilled	Partially collapse
4	Qixian-Linfen highway, Shanxi	50–200	1.8–3.5	28–60	1	Short-wall	1979–1999	30–60	Natural collapse	Unfilled	Partially filled	Partially collapse
5	Taiyuan-Jiuguan highway, Shanxi	100–150	6–8	15–20	1	Short-wall	1996–1998	40–60	Natural collapse	Filling ratio, 10–20%	Half filling	Partially collapse
6	Wu-kui highway, Xinjiang	24–47	0.7–3.0	15–30	1–2	Longwall	1990–1998	60–80	Natural collapse	Natural collapse	Fully filling	Partially collapse
7	Jin-jiao highway, Shanxi	20–70	1.5–6	15–45	1–2	Longwall	1970–1990		Natural collapse	Half filling	Half filling	Partially collapse
8	Fengjie-wuxi highway, Chongqing	50–160	0.3–0.4	150–400	3	Handpicking or shooting	In the 1980s, before 2008	80	Natural collapse	Half filling	Partially filled	Partially collapse
9	Yulin-shenmu highway, Shanxi province	50–120	3.0	15–40	1	Room and pillar		50	Natural collapse	Half filling	Unfilled	Partially collapse
10	Da-yun highway, section of Luocheng-xiajiaying, Shasnx province	15–55	2.6	5–20	1	Longwall			Natural collapse	Half filling	Unfilled	Collapse slightly
11	Tongling-tangkou highway, Anhui province	13–16	1.0–2.5	10–15	1	Mainly Room and pillar, or longwall locally	1989–2001	55	Natural collapse	Half filling	Fully filled	Partially collapse
12	Jinzhou-fuxin highway, Liaoning province	9–64	0.7–0.9	10–80	1	Small coal pit	1980–1986	77	Natural collapse	Half filling	Unfilled	Partially collapse
13	Jincheng-houma highway, Shanxi	198	2.5–5.0	40–80	2	Longwall			Natural collapse	Partially filling	Unfilled	Partially collapse
14	Pingding-yangqu highway, Shanxi	12–62	6	2–10	1	longwall	1985–2006	30	Natural collapse	Half filling	Unfilled	Partially collapse

Table 12 continued

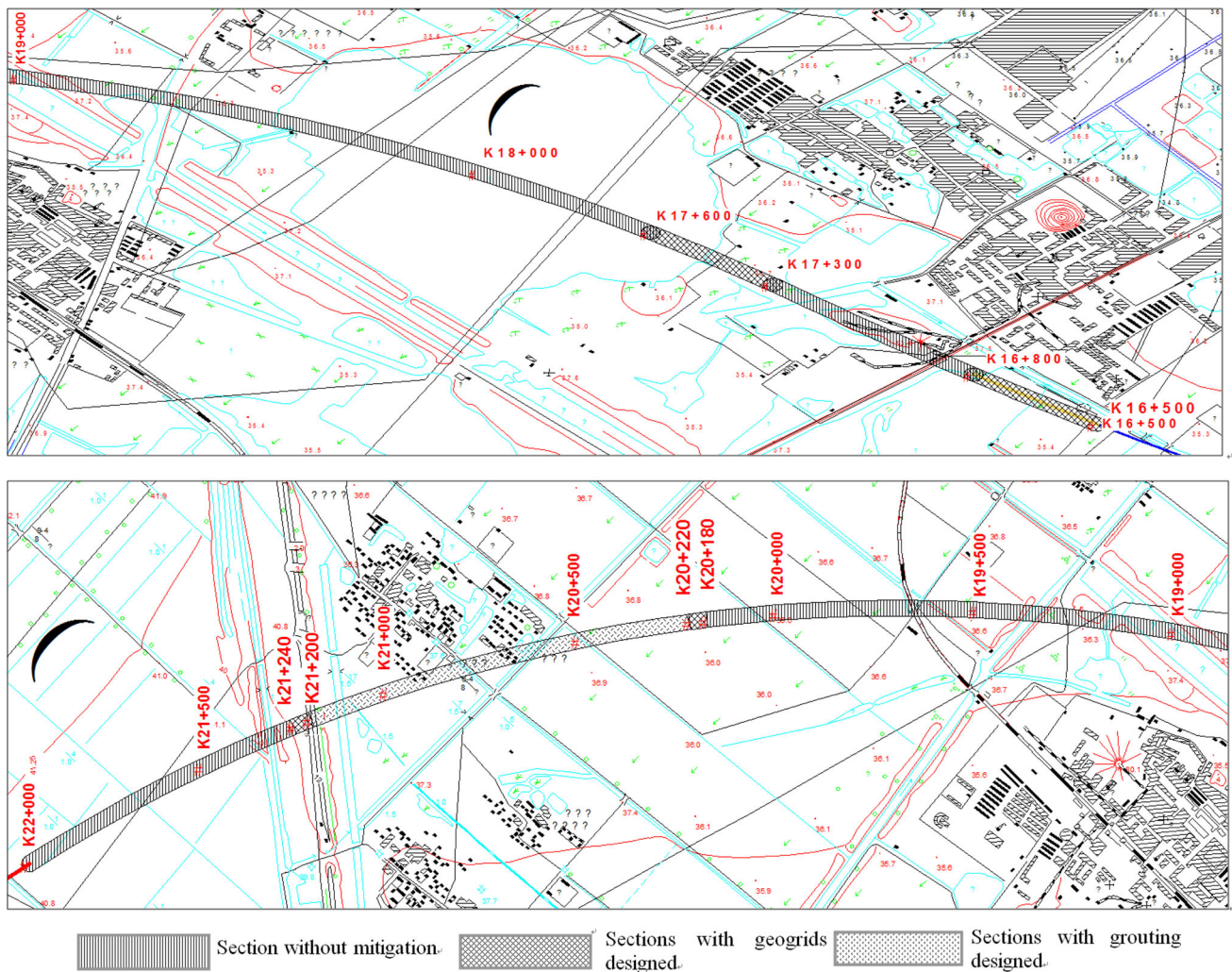
Case no.	Projects	Main characteristics of abandoned mines										
		Mining depth (m)	Mining thickness (m)	Mining depth-to-working thickness ratio	Mining layers	Mining method	Mining time	Extraction ratio (%)	Roof management way	Back filling condition of mine workings	Filling condition of residual voids	Collapse condition of mine workings
15	Handan-shexian highway, Hebei	40–200	0.43–0.6	80–350	1–3	Room and pillar, or longwall	In ancient times, 1985 and 2000 and between 1989–1994	30–35	Natural collapse	Half filling	Unfilled	Partially collapse
16	Shi-Tai highway, Shanxi	50–140	6–8	7–20	1	Short wall, or room-and-pillar	1989–1994		Large caving	Half filling	Partially filled	Partially collapse
17	Taiyuan-Changzhi highway, Shanxi	170–190	5–6	25–35	1	Longwall			Natural collapse	Half filling	Half filled	Partially collapse
18	Ma'anshan-chaohu highway, Anhui	5–13	0.5–1.7	5–15	1	Handpicking or longwall	1988–2000	60	Fully collapse	Unfilled	Half filed	Partially collapse
19	Zhengzhou-shaolin Temple highway, Henan	50–180	5–9	10–20	1	Room-and-pillar	In the 1990s	60	Natural collapse	Half filling	Unfilled	Partially collapse
Case no.	Projects	Exploration methods				Remedial measures						
		Exploration methods				Remedial methods						
1	Jing-fu highway, east ring of Xuzhou, Jiangsu	Geological and mining survey, geophysical exploration: high—density electrical method; high resolution shallow seismic reflection method, transient electromagnetic method, Radioactive radon gas exploration, borehole sonic wave testing, drilling				Flushing grouting method, using cement-flyash mixtures, total volume is 18,316 m <sup>3</sup>				266	25–98	
2	Dan-la national highway, section of Machangyuan-gaomiao, Qinghai	Geological and mining survey (route reconnaissance 40 km, geological mapping 0.62 km <sup>2</sup> )				Flushing grouting method, using cement-flyash mixtures, total volume is 15,901 m <sup>3</sup>				0–852	0–120	
3	Tai-lai, Tai-xin highway, Taian, Shandong	Geological and mining survey, geophysical exploration: TEM, high resolution shallow seismic reflection method				Flushing grouting method, using cement-flyash mixtures, total volume is 100,000 m <sup>3</sup>				5400	428–580	

Table 12 continued

Case no.	Projects	Exploration methods		Remedial measures	
		Exploration methods	Remedial methods	Treating length (m)	Treating depth (m)
4	Qixian-Linfen highway, Shanxi	Geological and mining survey, underground survey, TEM, drilling	Flushing grouting method, using cement-flyash mixtures, total volume is 39,119 m <sup>3</sup>	1285	50–180
5	Taiyuan-Jiuguan highway, Shanxi	Geological and mining survey, geophysical exploration: sasw, high resolution shallow seismic reflection method, Microgravity, TEM, soil radon, high density electrical method	Flushing grouting method, using cement-flyash mixtures, total volume is 56661 m <sup>3</sup>	730	100–150
6	Wu-kui highway, Xinjiang	Geological and mining survey, geophysical exploration	Flushing grouting method, using cement-flyash mixtures, total volume is 59,000 m <sup>3</sup> , Shallow ground improvement: heavy tamping 220 m; grouting 220 m	2075	24–47
7	Jin-jiao highway, Shanxi	Geological and mining survey, drilling, geophysical exploration: high density electrical method TEM	Flushing grouting method, using cement-flyash mixtures, total volume is 50,240 m <sup>3</sup>	1600	25–70
8	Fengjie-wuxi highway, Chongqing	Geological and mining survey, drilling	Flushing grouting method, using cement-flyash mixtures	1500	50–160
9	Yulin-shenmu highway, Shanxi province	geological and mining survey, drilling	Eolian sand filling (630,306 m <sup>3</sup> ) and cement-sand grouting	6030	50–120
10	Da-yun highway, section of Luocheng-xiajiaying, Shansxi province	Geological and mining survey, drilling	Flushing grouting method, using cement-flyash mixtures, total volume is 7050.5 m <sup>3</sup>	174	15–55
11	Tongling-tangkou highway, Anhui province	Geological and mining survey, geophysical exploration, drilling	Flushing grouting method, using cement-clay mixtures, total volume is 3705 m <sup>3</sup>	60	13–16
12	Jinzhou-fuxin highway, Liaoning province	Geophysical exploration, drilling	Flushing grouting method, using cement-flyash mixtures and cement-sand mixtures	372	9–64
13	Jincheng-houma highway, Shanxi	Geophysical exploration, drilling	Flushing grouting method, using cement-flyash mixtures, total volume is 77,000 m <sup>3</sup>	940	198

Table 12 continued

Case no.	Projects	Exploration methods		Remedial measures	
		Exploration methods	Remedial methods	Treating length (m)	Treating depth (m)
14	Pingding-yangqu highway, Shanxi	Geological and mining survey, drilling	Flushing grouting method, using cement-flyash mixtures, total volume is 77,028 m <sup>3</sup>	1000	12–62
15	Handan-shexian highway, Hebei	Geological and mining survey, drilling	Flushing grouting method, using cement-flyash mixtures and grouted rubble in tunnels	950	40–200
16	Shi-Tai highway, Shanxi	Geological and mining survey, geophysical survey, drilling	Flushing grouting method, using cement-flyash mixtures	730	50–140
17	Taiyuan-Changzhi highway, Shanxi	Geological and mining survey	Flushing grouting method, using cement-flyash mixtures, total volume 303,992 m <sup>3</sup>	1680	170–190
18	Ma'anshan-chaohu highway, Anhui	Geological and mining survey, geophysical survey, drilling	Flushing grouting method, using cement-flyash mixtures, total volume 18,562 m <sup>3</sup>	630	5–11
19	Zhengzhou-shaolin Temple highway, Henan	Geological and mining survey, drilling	Flushing grouting method, using cement-flyash mixtures	1100	50–180



**Fig. 8** Schematic mitigation design maps throughout the Puangzhuang Mine, Line B

particular highway alignment. Such practical assessment could result in measurable cost savings. Further, costs and operating procedures associated with special treatment techniques could have been incorporated into bid specifications of a particular section of highway, which may result in a more realistic estimate of project cost and duration.

**Acknowledgments** The authors are grateful to Prof. Yanjun Du at Southeast University, Nanjing, China, for the thorough review of this paper, and we also thank Prof. Fang Lei for helping us investigate the abandoned mines along the Highway.

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