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Geotechnical Engineering for Disaster Mitigation and Rehabilitation

INVESTIGATION ON THE NANJING GYPSUM MINE FLOODING

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Nanjing Gypsum Mine, or NGM, is encountering some engineering challenges in deep underground mining. The major challenges that affect the underground mine geomechanics and geoenvironment are attributed to groundwater, rock properties and geological structures, such as faults. A catastrophic mine flooding, triggered at NGM on 11 Sept. 2006, inundated the entire underground mine. The causes of this geological disaster are found multifold: hydrogeologically, the water-bearing karst rock overlain the orebody, the south of which was the direct water source of the catastrophic flooding; geomechanically, the low strength of the soft rock and the redistribution of mining induced stresses jeopardized the insitu balance and activated the discontinuities; and operationally, the inappropriate mining operation deteriorated the safety pillar and the ineffective seepage sealing method wasted the time for an effective measure to avoid the catastrophe. The mine flooding not only altered the underground hydrogeology, but also caused ground subsidence, damaged the surface structures and properties in the mine and its vicinity.

INTRODUCTION

Gypsum, mainly used in cements, ceramics, wallboards and plasters is one of the minerals available around the world. The USA is the largest producer of gypsum in the world; there are 48 gypsum mines distributed in 20 states in USA in Jan. 2006. Other countries with large gypsum productions, in descending order, are Iran, Canada, Thailand, China, Spain, Mexico, Japan and Australia (Founie et al., 2006). China is the 5th largest gypsum producer with a total reserve in excess of 600,000 million tons in 24 provinces, and currently about 500 mines in operation among which 70% are underground mines.

Room and pillar mining method is predominant in gypsum underground mines in China. But this method may not have been fully implemented in compliance with the mining legislations in some mines. One of the outstanding problems is that a large number of empty chambers are left without taking any appropriate ground controls. Such mined empty area is now totally in excess of 20 million m^2, and this figure is rapidly increasing. Other problems include inappropriate mining method, insufficient government administration and monitoring, and mining beyond the licensed zone in order to grab the mineral resource, which causes the deterioration and damage of the safety boundary pillars. On the other hand, with the rapid economic growth in China, the demand for gypsum is so strong that many mining companies are running beyond the production capacity, but the investment on the mining occupational safety and health hasn't matched the expansion of mining, resulting in frequent gypsum mine accidents with a trend of increasing fatalities in large accidents. The accidents are mainly caused by collapse of tunnels and stopes, and in particular, the roof fall of large area causes serious fatalities as tabulated in Table 1 are some recent accidents in gypsum mines in China.

Table 1. Fatalities in recent gypsum mine accidents in China

Name of mine	Date of accident	Type of accident	Fatality
Zhechen Gypsum Mine	28 Mar. 2000	Roof fall	5
Henda Gypsum Mine	18 May 2001	Roof fall	29
Xinglong Gymsum Mine	10 Nov. 2003	Roof fall of large area	5
Yetang Gypsum Mine	16 Feb. 2004	Roof fall of large area	6
Shangwangzhuang Gypsum Mine	6 Nov. 2005	Collapse	37

In addition to above geotechnical accidents in underground mining, mine flooding is another mine disaster that may be encountered in case that the groundwater inflow to the mine openings could not be stoped (Gendzwill et al., 1996; Zuber et al., 2000). Mine flooding may trigger a wide range of geoenvironmental problems, such as ground subsidence (Zuber et al., 2000; Perry. 2001), release of heavy metals (Biehler et al., 1999; Bain et al., 2001), alteration of geochemistry (Bain et al. 2001; Perry. 2001; Cidu et al. 2002; Donovan et al. 2003; Gammons et al., 2006), pollution of downstream groundwater (Bain et al. 2001) or surface water (Cidu et al., 2002). This paper presents an investigation on the cause of the catastrophic flooding at NGM in September 2006.

NGM BRIEF HISTORY

NGM, encompassing a land area of 1.29 km^2, is one of the well-known gypsum mines in China. It started the mine construction in 1971, began mining production at the sublevel -270m to -300m in 1984, when the design annual production was 300,000 tons. Since 1993, the sublevel -344m began to mine, and the production reached 400,000 tons per annum. By the end of 2004, NGM had mine 6.08 million tons of gypsum ore, and the production in 2004 was 423,200 tons.

The shaft-drive system is utilized for the mine development, room and pillar method for mining and shallow and/or medium blast-holes for blasting off the ore as shown in Figure 1 and Figure 2 (Zhu et al., 1994). Initially, the room was 8m wide, 8-9m high with pillar width 6m. Later on, the dimensions of the room was amended to 10m wide and 12m high, but the pillar width kept unchanged. By the time of the catastrophic flooding, the sublevels -270m and -308m were mined out but left untreated for ground controls. The flooding accident occurred at the sublevel of -344m, whose height is 30-34m.

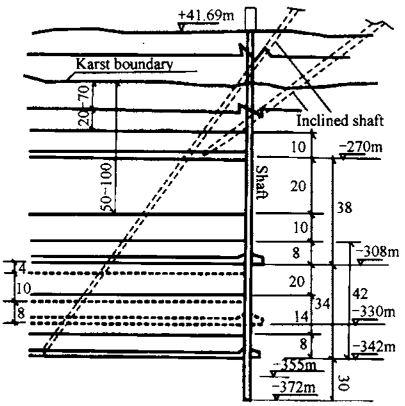


Figure 1. Excavation system sketch map of NGM

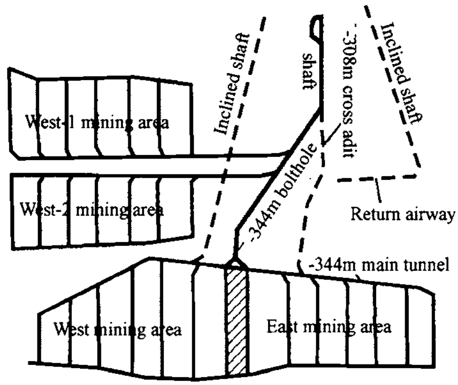


Figure 2. Sketch of –344m mining level and vertical shaft excavating

FLOODING ACCIDENT

A small inflow was first observed at No. 37 room on the sublevel of -344m on 19 June 2006. A professional grouting company was contracted to seal the seepage by underground grouting and construction of bulkheads, but unfortunately, the flow rate still gradually increased. By the end of Aug. 2006, it rose sharply from 0.00083 m^3/s to 0.0222 m^3/s. At about 12:30pm on 11 Sept. 2006, the catastrophic inflow of high pressure muddy water started to pour down after a 1.0m^3 wedge fell from the roof where the grouting workers were operating. In just two minutes, the water on the floor reached 25cm deep. By 3:30pm the workface on −344m was inundated. At 8:00pm, the water rose to -308m sublevel. At noon of 14 Sept. 2006, the water level reached to −270m sublevel. By far, the entire underground mine was flooded. It was estimated that the water flow rate was as high as 2.222m^3/s.

Such a large scale of underground mine flooding as NGM is very rare and devastating. It not only damaged the mining facilities, but also impacts a great deal to the local hydrogeology. The groundwater level was significantly dropped in the vicinity. For example, "the water level in some local wells dropped 1.5-2.0m in just one day." More seriously, the deep well that supplies portable water to the Huashu village dropped from -20m to -110m at the noon of 14 September 2006, causing the interruption of water supply to the villagers and the ground subsidence to varying degrees in different places.

GROUND SUBSIDENCE

On 12 Sept. 2006, ground subsidence, about a range of 1500m from the mine, was observed on the ground surface above the catastrophic inflow onset, causing such surface structures as roads and buildings damaged and ground cracked due to differential subsidence, many concrete pavements were cracked to 50 to 100 mm width. The cracks might be induced by tension or compression. Compressive cracks lead to the pavement detached from the subbase and formed triangular heaves of 20cm high. 40 houses in the Huashu village cracked, some of which were unsafe. The gypsum processing plant and the machinery maintenance plant of

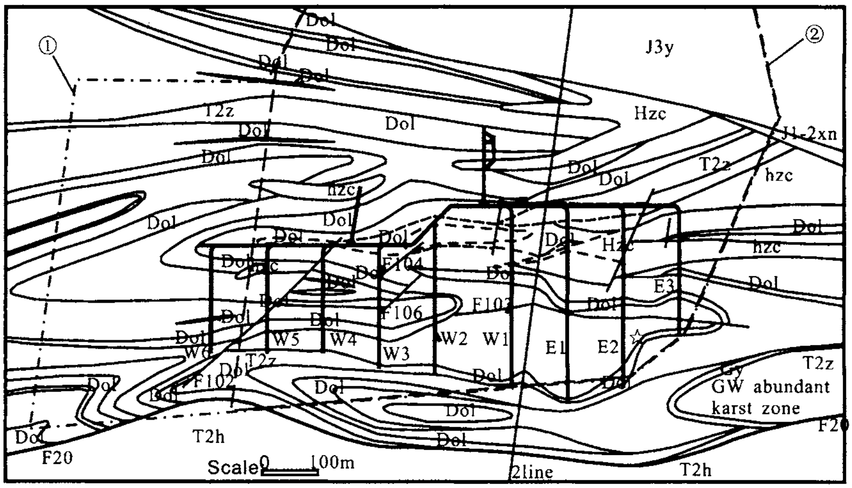
Huashu village were forced to be closed and evacuate the workers due to the ground cracked and the building damaged. The direct economic loss due to this disaster was estimated in terms of millions of Chinese Yuan.

No matter the crack is compressive or tensile, its strike shows an apparent tendency. In the northeastern of the mine, the concrete pavement was entirely sliding towards the mined area, indicating that the trough centre of subsidence is over the mined area. There were cracks parallel to the road, and the strike of the cracks ranged from 195° to 240°, dip from 285° to 330°. The ground subsidence and cracks were still developing on 14 Sep. 2006 when the geological disaster investigation commenced.

GEOLOGICAL INVESTIGATION

Geological structures

The terrain in the mine area is quite flat and the surface level is in 10s meter above the sea level. The surface soils are Quaternary residual and alluvial sediments of silt, silty clay and clay, with thickness ranging from several meters to 50 meters. The stratigraphy of the gypsum measures is depicted in Figure 3.



J3y, J1-2xn, T2h, T2z: The formation in mine area; Hzc: Melange;
Dol: Dolomite; Gy, Gypsum; ⁄: F20, Fault and umber; 2line: Section line;
①: Registered mining area ②: Mined area above-334m; W2: Sub-mining area

Figure 3. Horizontal section map of –344m deep in NGM area

The mine is located in a syncline whose axis is nearly in the east-west direction. The fold, also called Zhoucun-Huashu syncline, ranges from east to west 1300m, north to south 1440m and in the depth from –125m to –1100m. The upper part of the syncline is Jurassic basin, and the lower part is Zhouchong Group basin that encompasses the orebody. The two limbs of the syncline are asymmetrical, the southern limb strikes 340° to 20° and dips 30° with complete stratigraphy whilst the northern limb strikes 170° to 200° and dips 30° to56° with incomplete stratigraphy.

There are some faults in the mine area. The strikes of the majority of the faults are either parallel or perpendicular to the axis of the syncline. The perpendicular faults located in the Jurassic basin are small with little influence to the orebody. But the parallel faults in the Zhouchong Group basin are large, deep and concealed, such as F16, F18 and F20 in Figure 3 and Figue 4. Table 2 is the characteristics of F16, F18 and F20.

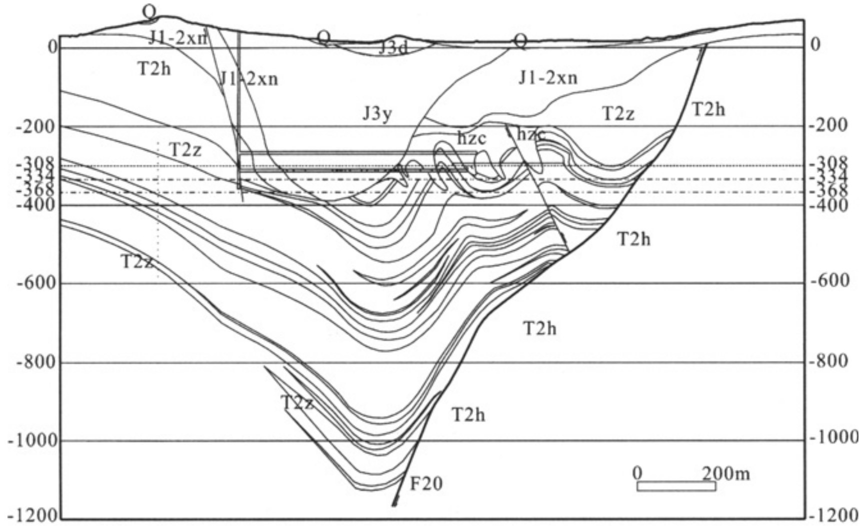


Figure 4. Typical geological profile of NGM area

Table 2. Characteristic of F16, F18 and F20 faults

Fault	Location	Attitude	Dimension	Description
F16	Crossing the syncline in south limb in the mine area	Dip: SE, Dip angle: 40° to 50°	Length: 2300m Extension: 280-320m	The fault zone is highly fissured, extremely karst, poor argillation, and strongly water-bearing. The permeability coefficient of the fault is as high as $0.01161m^3/s{\cdot}m$ of the specific capacity from pumping test
F18	In North limb of the syncline	Dip: South Dip angle: 60° to 70°	Length: 2500m Extension: 800-1100m	Exposed in No.2 shaft at –270m sublevel. Normal fault with throw of 30-40m. Fault breccia, cemented by clay and calcium, is impermeable with little localized water
F20	Passing the entire mine area in the southern	Dip: North Dip angle: 30° to 50°	Length: 2900m Extension: 1200-1400m	The strata T2z overlies on T2h. The hanging wall is consisted of anhydrite, limestone and dolostone, and footwall is clayey and silty sandstones. The fault zone is intact with some fissures cemented, impermeable and dry

Hydrogeology

In NGM area, the aquifers are generally slightly fissured except the fissured karst aquifer in Zhouchong Group, and the Quaternary aquifer is a relative aquitard layer.

The lower part of the Zhouchong Group is an aquitard, which is typically at the level of –600m or lower immediately overlain the orebody. The middle part is also an aquitard of 300m to 500m thick, which was evidenced by the fact that no water was observed from the investigation in the sublevel tunnels on –270m and –308m. The upmost part of the Zhouchong Group is an aquifer of 20m to 200m thick, with highly active karst typically ranging from 20% to 40% and up to 70%. From the pumping test, as the groundwater level was 5.947m to 8.587m, specific capacity was $0.00552-0.01740 m^3/s \cdot m$, hydraulic conductivity was $(0.894-1.767)\times10^{-4}$ m/s. Due to the aquifer is directly above the orebody, it is the major water source of inflows. The karst rate of the limestone in the mine and in its south ranges from 30% to 50%, so the limestone stratum is a reservoir of groundwater. The water in this aquifer is under piezometric pressure, typically from 50m to 200m and up to 450m, which is excessive to raise the water above the base of the overlying stratum. For example, during the excavation of the No.1 shaft at –298m, a groundwater-eroded cave was encountered. The sudden inflow of water at $0.083 m^3/s$ caused the stop of the shaft excavation. The unexpected inflow of water also occurred for several times during the mining operations at the two sublevels of –270m and –308m, the flow rate was at $0.042-0.056 m^3/s$, and the water was sourced from the southern karst zone.

There is a highly active karst strip of 570m to 650m wide and 75m thick in the Zhouchong Group in the southern part of the mine. There are huge water-eroded caves in the strip and the rate of cavity is 71.2%. From the vertical cross-section, the locations of highly active karst are typically in contact with the orebody. The degree of karst is clearly controlled by the geological structure.

During the construction, whenever the drilling encounters the karst limestone, there is a huge loss of washing liquid, collapse of the wall of the drill holes, and no other remedial measure can go through except for the cased drilling. Therefore, the karst aquifer is water-abundant and highly permeable, of high flow rate and under uniform piezometric pressure face.

Most drives are inside the gypsum orebody. The water inflow in the drives is mainly from the leakages at the cemented seals of underground diamond drill holes for hydrogeological explorations, which is caused mainly by the deterioration of the seal under the washing and eroding of groundwater.

The –270m sublevel and the No.2 shaft intersect with the F15 fault, but the flow rate of the fault is only $2.22-2.78 m^3/s$ since it locates in the Huangmaqing Group aquitard which is cemented by clay and of low hydraulic conductivity. From the historical statistics, the normal water pumping rate at sublevels –270m and –308m was among $0.0116-0.0162 m^3/s$ during the mine development phase, and the maximum rate was $0.0313-0.0509 m^3/s$ in case of a sudden inflow. The pumping rate at –344m sublevel is quite small during both the mine development and the mining operation phases.

Engineering geology

In the crown stratum of the orebody, the tuff sandstone and tuff breccia are weakly cemented with a low compressive strength of 2.8-6.3 MPa; the compressive strength of mixed conglomerate is typically 64.6 MPa; most of the water-eroded caves in the karst limestone are filled with clay, sand and gravel, and the compressive strength of the limestone varies among 32.4-60.8 MPa; at the interface, the compressive strength of gypsum is 8.8-12.8MPa, and this strength f breccia gypsum is 25.5-36.3 MPa.

The compressive strength of the orebody is very good except for some localized deteriorations due to fissures and joints. The compressive strength of the mixed conglomerate is 57.9 MPa at the interface between the crown stratum and the orebody, whilst it is 87.3 MPa in the orebody. The compressive strength of breccia gypsum from the orebody is 10.8-127.5 MPa in contrast with 25.5-36.3 MPa for the breccia gypsum from the interface.

The compressive strength of the sandstone in the southern bottom stratum of the orebody is generally above 87.3 MPa. The limestone in the northern bottom stratum is relatively intact. The compressive strength of the broken zone of the fault is very low, and it is even lower at the locations where the crown stratum is karst limestone.

DISTURBANCE DUE TO MINING

Engineering geological problem analysis for underground mining

Underground mining involves in the complex and dynamic engineering geological problems, such as stope stabilities, mine geological disasters, such as dynamic in situ stress and mine flooding, and mine environmental impacts, in particular, ground subsidence and crack.

Though the ground subsidence induced by mining can't be avoided, mine ground subsidence can be minimized and should be kept relatively stable during the lifespan of the mine and subsequent services (Singh. 1992; Holla et al., 2000). The major factors affecting the ground subsidence are the panel width of mining, depth and seam thickness. Other factors are mining method, sequence and rate, geological structures, discontinuities, groundwater and strength of overburden rocks and soils (Singh. 1992).

Pillars may fail due to spalling, shearing along discontinuities, multi-plane shearing and relative displacement between the pillar and the adjacent weak country rock (Brady et al., 2004), such failures may be affected by discontinuities, rock strength, blasting, slenderness ratio, and irregularity of the pillar, and eccentric loading on the pillar.

Tensile crack and peel-off of the roof is one of the roof failures (Yao et al. 1994). Tensile stress may be induced in the surface of the roof in the mined area, and the maximum tensile stress may occur at the midway between two adjacent pillars. As the tensile strength of rock is about 1/10–1/50 of the compressive strength, the roof is subjected to tensile failure in case of an unfavourable discontinuity, which in turn accelerates the growth of tensile crack on the roof. There are many factors that may affect the roof failure, such as insitu stress, uniaxial compressive strength, or UCS, of rock, rock quality designation, or RQD, groundwater, mining method, sequence and rate (Potvin et al., 2003; Jiang et al., 2004; He, 2005).

From the miningzone outwards, the rock mass may be divided into broken zone, plastic zone and elastic zone. Deep lying rock mass may respond differently, the broken zone and non-broken zone may occur alternately. When the initial vertical stress σ_{vi} is greater than UCS, this zoned broken phenomenon occurs. The number of broken zones depends on the ratio of σ_{vi} /UCS. The greater the ratio is, the more the broken zones are (Qian, 2004). Therefore it might be imperative to consider such phenomenon and the residual strength of rock when assessing the stability of deep rock structures. Does this phenomenon exist in NGM? This will be an issue for further studies.

Rocks, especially soft rocks, may exhibit creeping that is a phenomenon of the deformation of rocks increases with the time elapse under a given load. Both anhydrite and gypsum breccia demonstrate the characteristic of creeping. To initiate creeping, the stress needs to reach some level, and the process may consist of instant elastic strain, over creeping phase, stable creeping phase and accelerated creeping phase. Creeping will impact the long-term stability of the mined area (Liu et al., 2000; Song et al., 2005). The anhydrite and breccia-like anhydrite from NPM exhibit a similar creeping curve.

The stability, ground subsidence and sudden inflow of water in underground mines are controlled by the structural features of rock mass and local hydrogeology. There are a variety of discontinuities in rock mass such as bedding plane, fault, joint and fissures. The strength of the discontinuities is significantly lower than that of the intact rock, so they are controlling the strength and stability of rock mass. These structural features of rock mass play a decisive role in mine general design, mining method selection, tunnel design and ground control, etc.

The sudden inflow of water in the tunnels exists in NGM since the construction of the mine, but the stability issue has not yet been prone to the mine since a safety barrier pillar is designed between the allowed mining area and the water conducted fault and the water-rich intensive karst crown stratum, respectively. Meanwhile, the rock mass is not heavily jointed, so room and pillar mining and the shallow and/or medium depth blasthole blasting technique are productive for the mining operation in NGM.

The causes of the catastrophic flooding are, on one hand, controlled by the geological structures and hydrogeological settings. On the other hand, the mining operation has exceeded the prescribed safety boundary, disturbed the fault that connects to the karst aquifer in the crown stratum, and damaged the local stress and hydrogeology equilibriums. As a result, the roof and the pillar are subjected to the uncontrollable large deformations. The underground grouting and construction of bulkheads couldn't stop the catastrophic inflow and the subsequent ground subsidence and facility damage.

Effect of mining on the activation of faults and joints

As the local stress field is controlled by the fault and the joint distribution in the influence area of the fault, the stresses are redistributed due to the disturbance of mining, which may cause new joints and change the local hydrogeology. Sometimes, the broken zone of the fault may become a barrier of the stress-strain transmission, resulting in stress concentrations in the broken zone and in the rock mass between the fault and the workings. The presence of groundwater in rock mass has a significant effect on its physical properties, and the inflow from an aquifer is an important condition for the joint growth and rise of groundwater.

The activation of the deformation and hydraulic conductivity of the fault is a function of time and space. As the orientation, shape and scale of the faults are varying, so are the dimensions of openings, sizes of the hydraulic safety pillar and advance direction of the workface, consequently, the spatial distribution of the induced stress and strain are different. However, there are some rules to follow. The larger the dimensions of openings are, the greater the degree of redistributions of the induced stresses is. The closer to the fault, the more intensive the induced radial and tangential stresses are and the larger the influence area of the tangential stress would be.

The relative spatial position of openings to the fault also affects the deformation of the fault and changes the hydrogeology of the fault. If the direction of the induced tangential stress is opposite to the initial insitu stress, it will make the fissures in the shearing zone open more easily. The time factor of the induced stresses, fissure growth and rise of groundwater in the fault have critical effects on the activation of the hydraulic conductivity of the fault, and the advance rate of the workface is key factor controlling the time factor (Li et al., 2002; Li et al., 2003).

The likelihood that F20 in the southern part of the mine might be connected with the water-bearing karst zones in the crown stratum was considered in the 1st phase design of NGM, so a 200m wide strip along the full length of the fault, 1300m, was designed as the safety pillar reserve (Zhu, 1994). But the mining room was just 100m away from the fault when the flooding was triggered. At the early stage of the inflow prior to the catastrophic flooding, the broken zone of F16 was activated due to mining disturbance and the seepage pressure was estimated as 400 kPa, the flooding disaster in NGM might have been avoided if the mining operation had been immediately stopped and measures had been taken to reinforce the roof and walls and to seal the seepage by underground grouting and construction of bulkheads. However, in the reality, the single measure of grouting had failed to stop the seepage, furthermore it might have adversely enlarged the hydraulic channels to the karst water bodies and worsened the flooding disaster, consequently the large mine was ruined at a moment.

CONCLUSIONS

The catastrophic NGM flooding has not only changed the local hydrogeology, but also altered the geomechanics of the rock mass, resulting in the redistribution of the insitu seepage net and stress field. The sudden inflow of groundwater is firstly controlled by the geological structures, secondly by features of rock mass, hydrogeology and engineering geology. This was evidenced by the sudden inflows and seepages during exploring, constructing and mining.

At karst zones, especially the highly water-bearing ones, due to the distribution of discontinuities and water-eroded caves are not clear, employing the underground grouting technique not only failed to remedy the seepage, but to make things worse also, it might delay to reinforce the workface, resulting in the disaster unavoidable.

The ground subsidence induced by the underground flooding caused a range of damage to the surface facilities, including roads, houses and plants. The flooding dramatically lowered the groundwater level in the mine and its vicinity. As local villages and plants mainly live on groundwater, the flooding triggered an immediate interruption of water supply, which attracted a wide social and community attentions.

Local governments and research institutes have made an enormous effort for the disaster relief and rehabilitation, and an emergence steering committee consisted of governmental officers and experts was established right after the catastrophe. Warning signals were set up around the dangerous zones jeopardized by the flooding and subsequent ground subsidence.

Educational cards of the geological disaster were developed and sent to the villagers affected by this disaster as well as the relevant explanations and propitiations. Post diaster survey and monitoring were organized, and all surface cracks were measured, monitored and recorded.

As the ground subsidence may take a long time to be stable, a monitoring network was established on the ground surface in consideration of the distribution of underground old workings and the importance of the surface facilities, so that the tendency of the ground subsidence can be predicted in real time, and any dangerous signals can be immediately announced, so as to confine the disaster and reduce the injury and fatality.

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