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SYSTEMATIC APPROACH TO MITIGATE LONGWALL SUBSIDENCE INFLUENCES

Yi Luo

Abstract: The ground and surface subsidence process induced by longwall coal mining operations can cause adverse influences to subsurface and surface structures and water resources. Successful mitigation of these influences depends heavily on accurate assessment of the types, severities and locations of the subsidence-induced deformations and good knowledge of the structures. The most important step for mitigating subsidence influences is to accurately predict the dynamic and final movements and deformations in the area of interest. Based on the principle of influence function method, a series of subsidence prediction models have been developed for predicting dynamic and final surface and subsurface subsidence for longwall, room and pillar mining operations. The effects of inclined coal seam and steep surface terrains can also be considered the subsidence prediction. These prediction models have been validated with a large number of collected subsidence cases. With the accurately predicted ground deformations and good knowledge of structures, the types and severities of possible subsidence disturbances to the structures can be correctly assessed. For large and complicated structures, subsidence influences on structural stability, integrity and functionality have to be carefully considered. Once the causes and extents of the structural disturbances are identified, designing proper and cost-effective mitigation measures is often relatively easy. This systematic prediction-assessment-mitigation approach has been successfully employed in numerous applications.

INTRODUCTION

Subsidence associated with longwall mining operations generally has the potential to cause adverse effects to various surface and subsurface structures and water bodies. In order to cost-effectively reduce the severity of the subsidence influences, a systematic approach should be followed. The following three steps are involved in the approach: (1) accurate prediction of dynamic and final surface and subsurface movements (i.e., subsidence and horizontal displacement) and deformations (i.e., slope, strain, curvature, twisting and shearing), (2) accurate assessment of potential subsidence influences, and (3) properly designed and implemented subsidence mitigation measures.

In order to provide accurate subsidence prediction, mathematical and computer models have been developed for predicting dynamic (time-dependent) and final surface and subsurface subsidence associated with longwall mining operations. The developed subsidence prediction models have been calibrated and proven to be accurate innumerous cases of subsidence monitoring and structure mitigations. Various critical deformations have been derived and many assessment techniques have also been developed for assessing the potential and severity of subsidence influences to various surface structures. Techniques to mitigate the subsidence influences on various types of structures have also been developed and field tested. All the developed models and techniques have been used in a systematic way to predict, assess and mitigate longwall subsidence influences on surface structures.

Over the last two and half decades, this systematic approach has been improved and applied in mitigating: (1) over 300 residential structures ranging from simple trailers to large and complicated mansions as well structures on historic lists, (2) various buried water, gas, oil and sewage pipelines in varying pipeline material, sizes and constructions, (3) highways and railroads and their bridges, (4) various tower structures, (5) power substations, (6) reservoirs and dams, (7) investigation of various subsidence cases over inactive coal mines. In this paper, steps and techniques used in the systematic approach are presented.

SUBSIDENCE PREDICTIONS

The most important step for assessing and mitigating subsidence influences is to accurately predict the dynamic and final movements and deformations in the area of interest. Based on the principle of influence function method, a series of subsidence prediction models have been developed for predicting dynamic and final surface and subsurface subsidence for longwall and room and pillar mining

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operations. Expanding the principle, models to consider effects of inclined coal seam and steep surface terrains have also been developed. These prediction models have been validated with a large number of collected subsidence cases.

Final subsidence predictions

The principle of the influence function methods is used in developing mathematical models for predicting final surface and subsurface subsidence. The original influence function method (Knothe, 1957) is the backbone of the mathematical model for predicting final surface subsidence when both the extracted coal seam and surface are level or nearly level. It states that the extraction of an elemental area of an underground coal seam causes a surface point to subside in a particular manner. Generally, the point located directly above the extracted element receives the most subsidence. The farther the point is away from the extracted element, the less amount of influence is received. The mathematical function selected to represent the distribution of the subsidence influence caused by the elemental extraction is called the influence function. The final subsidence at a surface point is the result of all influences received at this point when the coal seam in the "mined area" has been extracted element by element. Mathematically, the final subsidence at a surface point is expressed as the integral of the influence function throughout the "mined area". The complete derivations of the mathematical expressions for the final surface movements and deformations have been presented elsewhere (Luo, 1989; Luo and Peng, 1989). In order to assure subsidence prediction accuracy, great effort has been made to monitor subsidence events and to collect subsidence cases from various sources. A set of final subsidence parameters have been derived from each of the collected cases and the empirical formulae have been developed for the parameters (Peng, *et al*., 1995). The combination of the sound mathematical model and the reliable subsidence parameters result in a proven final subsidence prediction model.

The principle of the influence function method lays out a good foundation for expanding it into the development of prediction models for various application conditions. It is a well-known fact that the characteristics of surface subsidence in hilly terrains could be very different from that on level ground. The first expansion of the influence function method was the development of a comprehensive subsidence prediction model to consider the hilly surface terrains (Peng and Luo, 1988; Luo and Peng, 1999). In this model, the additional surface movements, other than that normal subsidence expected on level ground, occur along the interface between the topsoil and bedrock and within the topsoil zone. The intensity of the terrain effects on ground movements depends on slope angle, thickness, wetness and mechanical property of the soil zone.

Longwall mining in inclined coal seams has been a common practice in some major coal mining countries. The characteristics of the final subsidence basin induced by longwall operation in inclined coal seams are different from that caused by mining in a level coal seam. An influence function method is developed for the prediction of the final surface movements and deformations over a longwall panel extracted in an inclined coal seam (Luo and Cheng, 2009). The German experience and the findings from subsidence research in the US have been combined in developing an asymmetric influence function as shown in Figure 1. The degree of asymmetry of the influence function is dependent on the angle of the seam inclination. The determination of final subsidence is performed through a modified scheme of integrating the influence function between the inflection points.

The subsurface strata movements and deformations induced by the longwall subsidence process could affect the stability of subsurface mine structures, surface water bodies and subsurface aquifers and the emission and migration of methane. In order to understand such effects, subsurface subsidence prediction methods have been developed using the concept of influence function method. The first version was developed based on surface subsidence theory (Luo and Peng, 2000). This model can predict final subsurface subsidence but it could not take the variation of overburden stratification into consideration. This model was enhanced later (Luo and Qiu, 2012). In the enhancement, the overburden strata over a longwall gob are divided into a finite number of layers of equal thickness. The percent of the hard rock strata (i.e., sandstone and limestone) in each of the layers is calculated and used as an input. The subsidence on the top surface of a given layer can be determined in the following procedure: (1) transforming the overburden load above it into a uniform equivalent load on the layer; (2) defining the subsidence influence function at a prediction point using the equivalent load, layer thickness, percent of hard rock and vertical movement at the layer bottom directly under the prediction point; (3) integrating the influence function within a proper horizontal interval for the final subsidence on the top of the layer. Therefore, the influence function is no longer a fixed function as in the previous models but varies with location and strata composition. The source causing subsidence of the current layer is the magnitude and distribution of the vertical movement directly under the layer. This procedure is repeated from the mining horizon, layer by layer upwards, until the ground surface is finally reached. Through this approach, the effects of the overburden stratification, especially the massive hard rock strata, on subsurface subsidence can be considered. In the subsurface subsidence prediction model, one new and useful deformation term, total strain, is also introduced and determined. The total strain reflects the volumetric change of the overburden strata at a given point.

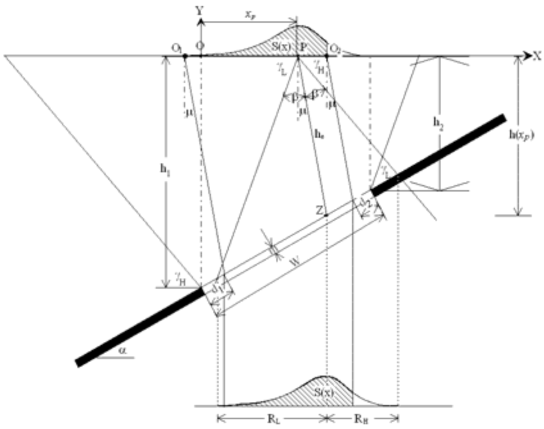


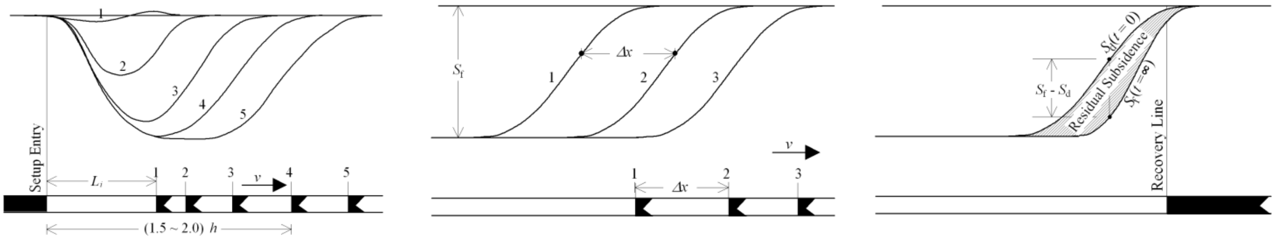
Figure 1: Diagram showing relations for using influence function method to predict final surface subsidence over a longwall gob in inclined coal seam

Dynamic subsidence prediction

For most longwall mining operations, the time-dependent dynamic subsidence process can bring more disturbances to common structures than the final subsidence. Based on field subsidence monitoring, the dynamic subsidence process associated with longwall mining operations can be divided into four phases (Luo, 1989; Luo and Peng, 1992). The first three phases are shown in Figure 2 in which the surface subsidence profiles and the corresponding locations of the longwall face are plotted. The first dynamic subsidence phase is the subsidence initiation and development process in the initial stage of mining a longwall panel. This phase is characterised as having no or little surface subsidence until the longwall face has reached a subsidence-initiation distance and it is immediately followed by a sudden and rapid subsidence process (Figure 2a). It should be noted that the disturbance power associated with this phase is much stronger than any other dynamic subsidence phase. In shallow mines, large ground cracks could often occur at locations a short distance inside the panel setup entry. The second phase is the normal dynamic subsidence process in which the portion of the subsidence basin on the face side advances with the longwall face while it moves toward the recovery line of the panel as shown in Figure 2b. The normal subsidence phase is the simplest among the dynamic subsidence phases and the shape of the dynamic subsidence basin on the moving face side is milder than the final one on the setup entry side. The third is the residual subsidence phase occurring after the longwall face stops advancing. It is a transitional process for the ground to subside from its normal dynamic state to its final stage (Figure 2c). Most of these three dynamic subsidence phases last from 10 days to one month in US longwall operations before the final subsidence at a point is reached. The last phase is the long-term dynamic subsidence phase that could last for years (Luo, *et al*., 1997; Luo and Peng, 2000). The causes for the long-term phase are re-compaction of the disturbed overburden strata and/or creep deformation of remnant mine structures. Generally, most of the long-term subsidence process is very minor and un-noticeable. However, the gradual failure of mine structures due to insufficient long-term stability (e.g., the chain pillar systems separating adjacent longwall panels) could induce significant long-term subsidence. Prediction methods have been developed for all these dynamic subsidence phases (Luo and Peng, 1992, 2000).

Based on the prediction methods, the following two subsidence prediction program packages have been developed.

Comprehensive and Integrated Subsidence Prediction Model (CISPM) is a computer program package for predicting surface the final and dynamic subsidence induced by underground mining operations conducted in a single coal seam. It predicts final subsidence basin for coal extraction in a longwall section of up to 10 panels, over an irregular (non-rectangular) underground opening (Luo and Peng, 1993), and the complete dynamic (time-dependent) subsidence process associated with longwall mining operations. It also provides services such as recommending subsidence parameters based on the site specific geological and mining information, deducing the final subsidence parameters from collected subsidence data, processing and managing subsidence survey data. This program package has been successfully employed in numerous application cases for assessing and mitigating the subsidence influences on various surface structures and environment.



a. Initiation Phase b. Normal Phase c. Residual Phase

Figure 2: Dynamic Subsidence Phases Associated with Longwall Mining Operation

Subsidence prediction programs

Comprehensive and Integrated Subsidence Prediction Model – Multiple Seam (CISPM-MS) is a program for the prediction of the final surface movements and deformations caused by mining operations in multiple coal seams (Luo and Qiu, 2012). The operations can be conducted using longwall and/or room and pillar mining methods. In the prediction, the final surface movements and deformations at a surface point caused by the individual mining operations in multiple coal seams are summed. The effects of Multiple Seam Mining (MSM) interactions on the stability of remnant mine structures based on subsurface subsidence prediction are assessed. The additional subsidence caused by the failed mine structures due to MSM interactions in sufficiently large continuous areas is determined and included in the final surface subsidence.

ASSESSMENTS OF SUBSIDENCE INFLUENCES

As a caving method, longwall mining operations induce immediate surface subsidence that is generally capable of disturbing surface structures, surface and subsurface water bodies to varying degrees. For surface structures, a longwall subsidence event can cause structural integrity, stability and functionality problems.The severities of these subsidence disturbances depend on the magnitude of ground deformations, the characteristics of the structures and the natural surroundings. In order to gain a good knowledge of the structural and surrounding information, a careful site visit should be made to collect information such the geometry, materials, construction, strength and weaknesses and existing conditions of the structures. The ground condition (i.e., slope, approximate depth and wetness of the soil zone) should also be checked and documented. The distribution of expansive total strain (or called void intensity) in the overburden strata plays an important role in determining subsidence effects on surface and subsurface water bodies. Accurately assessing the types, severities and timing of subsidence influences provides hints for generating effective mitigation plans.

Critical surface deformations

For most of the common surface structures, it is the ground deformations that cause the problems. Based on extensive monitoring of structural responses to subsidence process, various critical deformations have been derived for various types of structures. A critical deformation is the minimum deformation to start a structural problem.

Subsidence-induced surface strain, especially tensile strain, is responsible for most of the integrity problems to the structural parts that have direct contact with the ground such as foundations, basement walls, and the lower part of building walls. The critical strains are:

- Cracks on soil surface: 1.2×10^{-2} m/m (ft/ft)
- Cracks on asphalt surface: 1.0×10^{-2} m/m (ft/ft)
- Cracks on concrete pavement: 2.0×10^{-3} m/m (ft/ft)
- Cracks on stone walls: 3.0×10^{-3} m/m (ft/ft)
- Cracks on brick and concrete-block walls: 2.0×10^{-3} m/m (ft/ft)

Curvature often is the second largest contributor to the integrity problems on the common structures, especially the super-structures. Curvature normally would have little effects on small structures. For typical residential structures, a curvature larger than 2.0×10^{-4} 1/m (6.0×10^{-5} 1/ft) could cause hairline cracks at building corners and joint lines and step cracks at the corners of doors and windows, etc.

Subsidence-induced surface slope could affect the stability of tall and slim structures such as chimneys, silos, towers. For residential structures, high slope (> 1%) could make them uncomfortable to live and could render their drainage systems unworkable. Compared to the permissible grade of 0.7% for railroad operation, the maximum subsidence-induced slope associated with longwall operations can easily disrupt normal railroad operation.

Residential and farm structures

For most residential and farm structures, the potential subsidence influences can be assessed by comparing the predicted deformations to the derived critical values while considering the dimensions, complexity, existing conditions, construction materials and methods. If a structure is located on or near long and steep sloping ground, the potential influences from the topography effects should also be assessed. Under certain conditions, the topography effects could be even stronger than those caused by subsidence alone. The assessments are normally conducted in two separate steps. The first step is to assess the potential influences caused by the predicted final surface deformations that will be permanently imposed on the surface structures. Final subsidence-induced problems normally occur in a zone along the panel edges. The second step is to assess the potential influences from the dynamic subsidence process. The structures located over the panel setup entry and the "central" portion of the panel will experience a significant time-dependent deformation process. The typical ground dynamic deformation process can be divided into two half stages. In the first half, a ground point will go through a process of increasing tension, maximum tension, decreasing tension and maximum slope. In the second half, the point will experience an increasing compression, maximum compression and decreasing compression process. Normally, convex curvature is accompanied with tensile strain while concave curvature goes with compressive strain. The first half of the dynamic subsidence is much more critical to common surface structures than the second half. In addition to the magnitudes of the maximum deformations, the locations from where the destructive deformations originate should also be identified.

Industrial and public structures

Industrial and public buildings include large workshops, telecommunication towers, power transmission towers and transformer stations, water towers or tanks, bridges, office and school buildings. For large structures with special purposes, the assessment of subsidence influences could be much more complicated than that for residential structures. These structures could be significantly different in structural designs and constructions as well as function tolerance limits. Accordingly, the assessment techniques for each type of structure could be different from the others. Therefore, in the stage of pre-mining site visit and information collection, detailed information about the structure and its performance limits should be obtained. Since most of these structures are large and inflexible, the subsidence-induced surface strains and curvatures are often fully capable of causing structural integrity failures such as cracks on and severe deformations of structural parts. Losing the intended structural functions is often the main concern for these structures. For example, telecommunication towers' long-distance signal relay function could be affected by subsidence-induced surface slope and differential horizontal displacement. The stability of tall structures with small bases during and after the subsidence process should be carefully assessed using the predicted subsidence-induced surface slope. Generally, most of the longwall subsidence events are unable to move the center of gravity of a tall structure out of its base. However, an inclined tall structure due to subsidence influence may have a reduced capacity to resist the force of strongest wind to be experienced and the stability under such condition should be assessed. The techniques to assess subsidence influences have been presented in other publications (Luo, *et al*., 2003, 2005; Luo, 2008).

Linear structures

Longwall subsidence could induce adverse influences to linear structures such as highways, power transmission lines, railroads, overland conveyors are buried pipelines. Among these linear structures, railroads, overland conveyors and buried pipelines are generally more prone to be adversely affected by longwall subsidence than the others because of the structural complexity and stringent performance tolerance limits. For highways, tensile strains higher than 2.0×10^{-3} and 1.0×10^{-2} m/m (ft/ft) could create cracks on concrete and asphalt pavements, respectively. High compressive strain (>3.0×10^{-3} m/m or ft/ft) can create bumps on the asphalt pavements. For highways with a large gradient (e.g., >5%), the subsidence-induced slope could make driving unsafe if the speed limit is not lowered. For railroads, the subsidence-induced strain and curvature can affect the integrity problems to the railroad structures. The slope can easily affect the operability of rail traffic. Mine subsidence events can cause significant damages to highway and railroad bridges and affect the safety of their traffic (Luo and Peng, 1994). A subsidence event can induce significant additional stresses on buried pipelines. Methods to estimate stress distribution along buried pipelines have been recorded by (Peng and Luo, 1988; Luo, *et al*., 1997; Qiu and Luo, 2013). The methods have been developed and have been successfully applied to assess the subsidence influences to pipelines of various sizes, pipe materials, and transmitted media. Generally, the ground strain and curvature contribute the majority of the additional stresses on the pipeline.

Water bodies

Surface water bodies (i.e., streams, ponds, reservoirs) and subsurface aquifers could be impacted by longwall subsidence. The two significant subsidence influences to surface water bodies are dewatering and water pooling. To the subsurface aquifers, the influences could be temporary (able to recover some time after the subsidence event) and permanent water losses (Luo and Peng, 2010). In flat surface area or along steam valleys with gentle gradient, a longwall subsidence event can create surface water pools. The severity of other subsidence influences on surface and subsurface water bodies depend on the magnitude and distributions of the subsurface deformations, geological and hydrological system of the overburden strata. The subsurface subsidence prediction model provides a good tool for studies of the effects of longwall mining on the hydrological system. The subsurface expansive total strain (volumetric expansion of subsurface strata or void intensity) indicates the total voids in a unit volume of subsurface strata induced by the subsidence. Figure 3 shows that predicted distribution of subsurface total stain over a longwall gob. Apparently, expansive total strain is mainly concentrated in zones located a short distance inside the panel edges.

Since water loss would not occur in the continuous deformation zone in the overburden strata, the maximum void intensity at the upper limit of the fractured zone can be used as the critical value for assessing the subsidence influences on the subsurface hydrologic system. Based on the results of water drawdown tests in more than 200 boreholes in 27 Chinese coal mines (Liu, 1981) and subsurface subsidence prediction, the critical void intensity for significant water loss is determined to be 4.1×10^{-2} m/m (ft/ft). It indicates that when a block of rock expands 4.1% more than its original volume, the voids inside the deformed rock would allow a significant amount of water to flow through it. When a contiguous zone with void intensity higher than the critical value intersects with either a surface water body or an underground aquifer, significant water loss could occur through this zone into the longwall gob causing permanent loss of the water body.

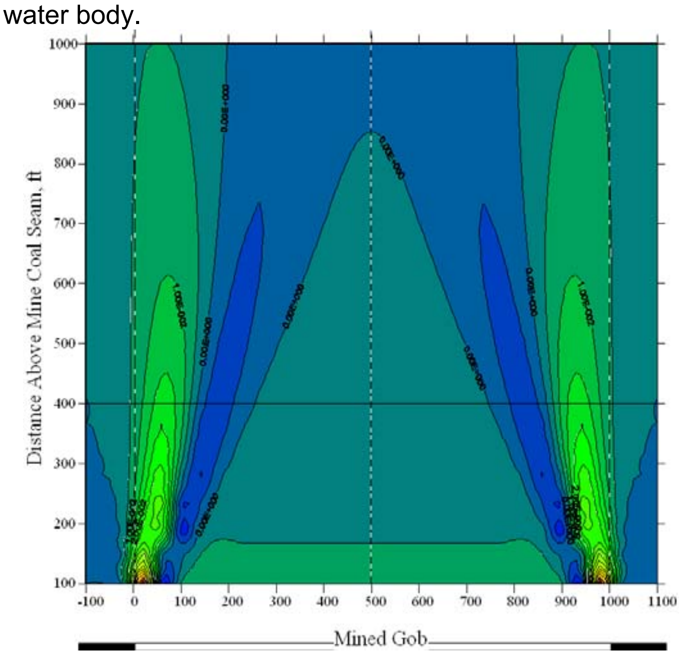


Figure 3: Predicted subsurface total strain over a longwall panel

In order to facilitate the quantitative evaluation of the water loss, subsidence-induced permeability in the overburden strata should be estimated. Under the influence of mine subsidence, the permeability at a given subsurface point (K) affected by subsidence is linked to the total strain (ε_t) by Equation 1. In the equation, K_o and ϕ_o are the original permeability and porosity before subsidence. An example of using the subsurface subsidence prediction model in numerically assessing the effects of a longwall mining operation on a surface reservoir is shown in a publication (Qiu and Luo, 2013).

$$K = K_o \left(\frac{1 + \frac{\varepsilon_t}{\phi_0}}{1 + \varepsilon_t} \right)^3 \quad (1)$$

MITIGATION MEASURES

Various mitigation measures has been developed and applied to reduce subsidence influences on numerous surface structures and water bodies. Properly selected, designed and implemented mitigation measures can greatly reduce and even eliminate the anticipated subsidence influences.

Mitigation methods such as compensation trench, tension cable or rope, plane fitting, internal and external bracing are commonly and successfully employed to protect subsidence influences to common residential and farm structures. Properly designed and constructed compensation trenches can be used to reduce the severity of the subsidence-induced disturbances to structural parts having direct contact with ground such as structural foundation, basement walls and floor pavement. A well designed compensation trench creates a weak plane between the structure and the strain-generating ground as shown in Figure 4. The weak plane reduces the transmission of ground strain from the strain-generating ground to the structure and then the severity of the structural problems on the ground-contacting structural parts.

The tension cable method is suitable for structures that have relatively high compressive strength such as stone, concrete-block and brick structures or structural parts. The structure to be protected is wrapped with pre-tensioned steel wire cables at properly selected locations and with proper tensions (Figure 4). The tension cables can serve two purposes: (1) the tension forces applied by the cables place the structure into a compression state so that it is able to compensate some of the subsidence-induced final or dynamic tensile stresses, and (2) the rigidity of those structural parts is increased so that they can tolerate higher deformations transmitted to it. The tension cable method can also indirectly reduce the severity of the anticipated problems on the super-structures caused by dynamic and final surface curvature if the deformation on the structural part under the super-structure can be effectively controlled. For weaker wood structures, the tension rope method serves the same purposes as the tension cable.

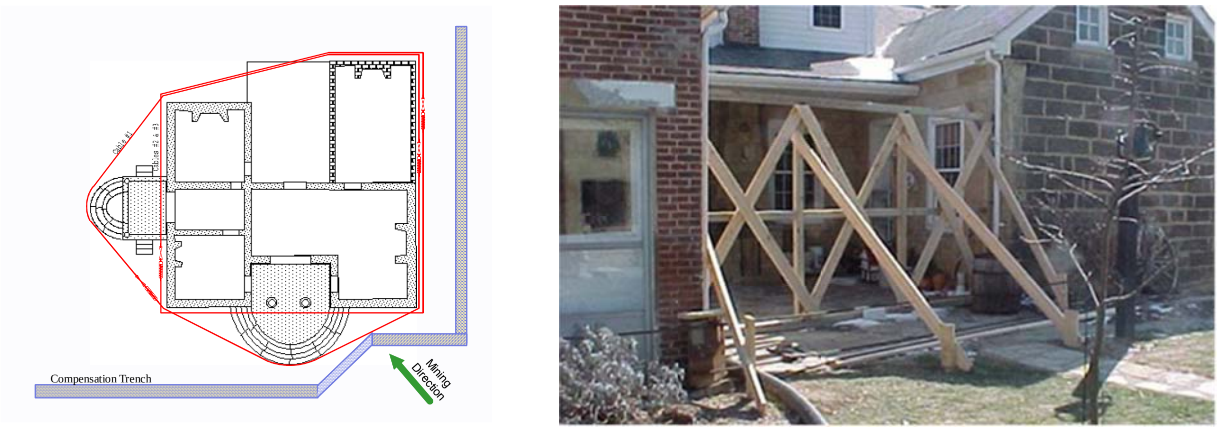


Figure 4: Mitigation Measures for a Historic House Located over the Central Portion of a Longwall Panel

The plane-fitting method (Luo and Peng, 1991) is a method to reduce the severity of disturbance to super-structure. It is particularly effective for structures that would experience a very intensive dynamic subsidence process such as those located over the central portion of subsidence basins over shallow mines. Height adjustable devices are strategically placed under the super-structure and their heights are adjusted constantly according to the measured subsidence and a mathematical algorithm so that the super-structure is placed on a time-dependent inclined plane at any given time. By doing so, the protected structure is stress-free. In determining the desired inclined plane at a given time, the total amount of required adjustment should be minimised.

The external or internal bracing method is used to reinforce the weak spots (e.g., large doors, windows and indent parts.) of the structure. The bracing structures such as wood frames or steel beam should have good compression stiffness to resist any significant closure of these weak spots. Figure 4 shows an external bracing structure used to prevent potential closure of two wings of a U-shaped structure while tension cables were applied.

For large and linear industrial/public structures, the mitigation measures could vary considerably. In assessing subsidence influence on buried pipeline, it is found that the majority of the stress (>80%) on the pipeline is caused by strain transmitted to the pipeline (Luo, *et al*., 1997). Since the ground strain is transmitted to the buried pipeline through friction force, reducing the friction force between the burial soil and the pipeline will be the most effective way to reduce stresses on the pipeline. Uncovering the pipeline is the most effective way to reduce the friction force. In order to reduce the amount of the required mitigation work and to avoid unnecessary artificial disturbance to the buried pipelines, partial uncovering method has been proposed to uncover only the sections of pipelines where the estimated stresses exceed the permitted stress of the pipe steel. This partial uncovering method has been successfully employed in protecting numerous and varying types of buried pipelines.

Longwall subsidence can induce sufficient deformation that can cause structural damage to the railroads and affect the safety of rail traffic. In order to reduce the severity of such subsidence influence, it is ideal to lift the railroad track back to its original level as it is subsiding. However, it is often impractical to do so because of the limited window of time between railway traffic or the limited rail base space for placing the required additional ballast. A partial lifting method has been proposed and successfully employed to maintain the railroad operational under such limitations (Luo, *et al*., 2010). The essence of the partial lifting method is to raise the subsiding railroad track at a given time only a determined partial amount of the subsidence so that the rail tracks can be maintained on a smooth and operational profile. The required adjustment is made by adding ballast under the track. The application of this method requires a careful pre-mining planning based on the simulations of dynamic and final subsidence predictions. When implementing the method, a daily subsidence survey is required. The measured ground movements are used to generate an adjustment plan that can be made within the available window of time based on a special algorithm. The most recent application of this method was on a 2,400-m long section of railroad located over two longwall panels (top left photo in Figure 5). In this case, the railroad experienced a maximum subsidence of 1.524 m (5 ft). The coal trains were safely operated in two-hour intervals while it was subsiding. Figure 5 also shows some of the large and important structures that were affected by longwall subsidence and have been successfully protected with the systematic approach.

Figure 5: Examples of mitigated surface structures using the systematic approach

CONCLUSIONS

Longwall mining operations induce immediate and intensive surface and subsurface movements and deformations that could cause adverse effects to surface and subsurface structures and water bodies. A systematic approach, including accurate subsidence prediction, correct assessment and effective mitigation of the potential subsidence influences, has been developed and successfully applied to protect numerous surface structures over longwall mines. The application of this approach has been proven to be cost effective to the mining companies and helped to improve the public relations with local residents.

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