SDPS for Windows: An Integrated Approach to Ground Deformation Prediction

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Abstract

The latest version of the Surface Deformation Prediction Software (SDPS) package is presented through its application to a number of case studies. The package now exploits all the benefits of the Microsoft Windows platform and has a direct interface to CAD software, thus facilitating input and output. Also, the package features advanced calibration routines to handle predictions over specific regions. The case studies presented highlight the features and capabilities of the new package.

Introduction

The impacts of underground mining on the surface are important environmental considerations in the permission, planning and monitoring of coal mining operations. As a result, the development of rigorous and well-accepted ground deformation prediction techniques, for assessing mining impacts on surface structures and facilities, is an important issue in subsidence control. This task can be extremely complex, due to the number and nature of the parameters affecting ground deformation induced by underground mining, including subsidence parameters, surface morphology, mine plan, coal structure characteristics, overburden lithology and the type of surface facility to be protected.

The Surface Deformation Prediction Software System (SDPS) is an integrated package for calculating a variety of surface deformation indices, using both the profile function and the influence function methods. These calculations are based on several empirical relationships, developed through the statistical analysis of data from a number of case studies (VPI & SU, 1987 & 1999; Karmis *et al.*, 1989, 1990 & 1992).

Basic Principles

Surface subsidence is an important environmental consideration of active, as well as abandoned, mine operations. The damages attributed to this phenomenon include land settlement and fracturing, structural damage to surface building, or disruption of ground water reservoirs. The prediction of ground movements due to underground mining, the assessment of their impact on the surface and, finally, their control within acceptable environmental limits, are all important considerations of underground coal mining. Although a detailed discussion on the basic principles of mining subsidence is beyond the scope of this paper, since it has been well documented in the literature, it is important, to present certain basic subsidence concepts and definitions (Figure 1).

- The surface area above an underground excavation within which ground movements are measurable (i.e., 0.6% Smax) is called the **influence area**.

- Angle of Influence (β) : It is the angle between the horizontal and the line connecting the projection of the inflection point position of the subsidence trough, at the seam level, with the surface point of "zero influence" i.e. where subsidence is about 0.6 percent of the maximum subsidence value (VPI&SU 1987). This is one of the basic parameters used in the influence function method of subsidence prediction (VPI&SU, 1987; Karmis *et al.*, 1990).

Surface movements caused by underground mining are usually described by a number of parameters, including the following:

- The maximum subsidence (Smax).

- The inflection point (I.P.): The inflection point corresponds to s = Smax/2 on the subsidence profile or zero curvature (i.e., the transition point from positive to negative curvature), and, therefore, is the point where the subsidence profile changes from concave to convex. This point is usually displaced from the rib of the excavation at a distance, (d) towards the panel center.

- The maximum tensile and compressive strains (Emax)

The mining induced factors which control the magnitude and propagation of ground movements can be broadly divided into two categories (Shadbolt, 1978):

- **Mining Factors:** Relate to the mining methods and the geometry and dimensions of the excavation, e.g. panel width and depth, method of support, extracted height, rate of advance, etc.

- **Site Factors:** Refer to the geotechnical conditions influencing mining subsidence, such as type of strata, soil properties, geological discontinuities and hydrology. Other factors

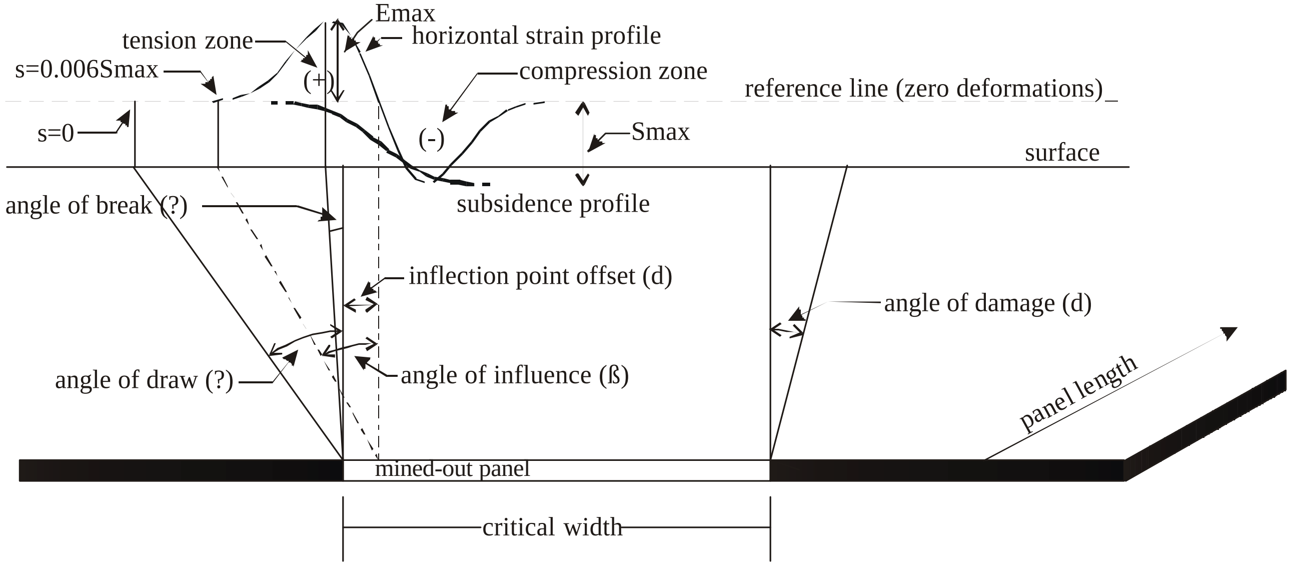

Figure 1. Definition of Subsidence Parameters

included in this category are previous workings and other man-made disturbances in the vicinity of the area of interest.

- **Structure Factors:** Should also be considered when dealing with possible damage to structures. Such factors may include size and shape of the structure, type of foundation, construction method, etc.

Subsidence Prediction Techniques

Subsidence planning and control requires pre-calculation or prediction of the most important parameters of surface movements that may cause structural damages. Only after such predictions have been made, successful subsidence control becomes feasible. In recent years, numerous research efforts have been undertaken in the U.S., as well as in most coal producing countries, to develop prediction methods dealing with the extent, magnitude and other characteristic parameters of subsidence. These efforts are well documented in the literature (Karmis *et al.*, 1989, 1990, 1992, 1995; VPI&SU 1987, 1994)

SDPS Software

The latest version (version 5.x) of the Surface Deformation Prediction Software was developed specifically for the Microsoft Windows environment. It is an integrated package for calculating a variety of surface deformation indices using both the profile function and the influence function methods and can be easily interfaced with pre- and post-processing software. Calculations are based on several empirical relationships, developed through the statistical analysis of data from a number of case studies (VPI&SU 1987, Karmis *et al.* 1990 and 1992), which include:

- a correlation of the maximum subsidence factor with the width-to-depth ratio of a panel and the percent hard rock (%HR) in the overburden,
- a correlation of the distance of the inflection point from the rib of the panel, with respect to the width-to-depth ratio of the panel,
- a regional value for the tangent of the influence angle (tanβ) and the radius of influence, and
- a regional value for the horizontal strain coefficient (Bs).

The profile function model can calculate subsidence values along a line perpendicular to the rib of the excavation area. The parameters used for the calculations include a measure of the average overburden characteristics, as well as the width, depth and extraction height of the mined-out panel (Karmis *et al.*, 1992). Also, two profile function curves have been developed: an average curve and a conservative curve. The conservative curve predicts a worst-case scenario profile, and extends the influence over a wider area. Statistically, this represents an envelope line of all possible subsidence occurrences in any given panel. The average prediction, on the other hand, is less conservative, in the sense that it predicts average values for which a deviation may be expected. Prediction points are positioned on a transverse line across the panel, from the point of maximum to the point of zero subsidence. The empirical parameters required for the calculations are already built into the profile function (VPI&SU, 1994).

The influence function method can model very complex mine layouts and can calculate a number of deformation indices, including: subsidence, slope, horizontal strain, and surface curvature at any point on the surface or at any other elevation above the extracted seam (Karmis *et al.*, 1990).

Finally, it should be emphasized that the SDPS software has been tested extensively and has given excellent correlation between predicted and actual measured subsidence and horizontal strain values, for a number of case studies (VPI&SU, 1987; Karmis *et al.*, 1989).

Case History – Longwall Mining Beneath a High Pressure Gas Pipeline

This case history involves the prediction of ground movements initiated by longwall mining beneath a twenty-six (26") inch high pressure (700 lb/in^2) gas transmission line. A temporary suspension of operations while the line was undermined was not an option. Therefore, the primary objective of the project was to raise or lower specific sections of the transmission line in response to the timing and magnitude of predicted ground movements. The transmission line crosses the head-end of two longwall panels, (7NW and 8NW) at an angle. Mining of the panels was projected to take place over a nine-month period with 7NW being followed by 8NW.

Subsidence prediction methods are basically developed to calculate the final subsidence profile. It is reasonable, however, to assess the dynamic profile by an iteration of successive steps simulating the dynamic development. Accepting this assumption, the SDPS was used to predict subsidence and ground behavior on increments of the seventy (70') foot estimate of horizontal daily face advance. The SDPS Initially, the SDPS model was calibrated using surveyed subsidence data provided to Appalachian Mining & Engineering, Inc. (AME) by the coal company. The data was obtained from detailed subsidence studies of residential structures undermined on previous panels. Subsidence predicted using SDPS was compared with the surveyed field data to determine the anticipated error for the 7NW and 8NW panels. Once the SDPS input parameters were calibrated using site data, the average error was 2.60 inches for a maximum ground movement of 3.69 feet or 4.62%.

Prior to subsidence calibration and modeling, a base map of the surface and underground features was developed in AutoCAD format using state plane coordinates. This information included:

- the basic geometry of the mine layout, overburden characteristics and geology,
- the pillars and longwall gateroad projections and the coordinates of survey points located along the gateroads of the subject longwall panels,
- the coordinates of survey stations used in the analysis of residential structures,
- the bottom of excavation elevations,
- the mining heights,
- the mine timing,
- the core logs and core hole locations,
- the gas transmission line location, and
- the projected rate of daily average face advance.

The longwall panels 7NW and 8NW were stationed in accordance with the mine so that the face advance and position used in the SDPS analysis would correspond with the mine surveying.

Calibration of the SDPS Subsidence Model

The SDPS program uses regional Appalachian coalfield averages for the tangent of the influence angle (2.31) and percent hard rock (50%) in conjunction with the actual panel geometry to estimate surface subsidence. Site-specific subsidence data greatly increases the accuracy of subsidence prediction and enables validation of the output data. Three (3) residential sites were the subject of detailed subsidence monitoring for an unrelated study. Data from these sites was chosen for SDPS calibration because of their close proximity to the gas transmission line. Data included in these studies came from control stations surrounding residential houses overlying the 10th West longwall panel. The survey control stations at the sites were surveyed as the 10th West longwall panel approached, passed beneath, and retreated from the homes.

The actual calibration and determination of site-specific input data was accomplished by entering measured subsidence data into the SDPS program. Based upon the known subsidence at the surveyed locations, input values were obtained through back calculation. Various combinations of the tangent of the influence angle and the subsidence factor were used in several hundred iterations to calculate the magnitude of subsidence. After each iteration, an error index is calculated by squaring the difference between the SDPS calculated value and the measured value for each point, and then summing the squared differences obtained at each measured subsidence point. The combination of tangent angle of influence and subsidence factor that produces the minimum error index is then used to fix the appropriate edge effect. As the tangent angle of influence and the subsidence factor are used to accurately model the magnitude of subsidence, the edge effect is used to define the position of the inflection point of the subsidence curve in relationship to the panel rib.

The edge effect incorporates the cantilevering of the overburden strata over the longwall gob to define the rate or slope of subsidence between the area of maximum subsidence in the center of the panel and point of zero subsidence outside the panel. The edge effect is adjusted until the slopes of the predicted and measured subsidence contours mimic each other. This procedure is repeated until the minimum error between measured and predicted subsidence has been obtained and the contours of predicted and measured subsidence agree as closely as possible.

This calibration methodology was used with measured subsidence data from the first residence. A total of ten (10) survey monuments were placed around this site. Monuments were placed at the four corners of the residence and the remaining six (6) were located in the surrounding yard. The minimum prediction error was 4.69 ft^2, which corresponds to an average error of 2.60 inches for each of the ten (10) measured subsidence points. Those subsidence parameters that produced the lowest total error of 4.69 ft^2 were:

- tangent of influence angle (2.90),
- subsidence factor (59.50%), and
- edge effect (77.50 ft.).

These subsidence parameters along with the percentage of hard rock as obtained from the coreholes, mining height, and longwall panel layout were used to model the subsidence and ground movement beneath the twenty-six (26") inch gas transmission line.

A map of the first residence showing the measured subsidence contours along with the calculated subsidence is shown in Figure 2. The maximum surveyed subsidence is shown adjacent to each point as well as contours of the subsidence predicted by SDPS and the actual subsidence are also shown in Figure 2.

The parameters calibrated at the first site were evaluated against subsidence survey data at the latter two sites. These residences overlie solid coal pillars, experienced minimal subsidence, and were further from Panels 7NW and 8NW than the first site. The subsidence control stations at the second and third residential sites had less than 0.08 feet (1.00 inch) of subsidence with the exception of one control station at the second site that had subsidence of 0.19 feet (2.28 inches). The surveyed subsidence data was compared with SDPS calculated values contoured on 0.10 feet intervals. Results show that the SDPS calculated values were within less than 0.10 feet (1.2 inches) of the measured survey data.

SDPS Subsidence Modeling

Surface subsidence, horizontal strain, horizontal movement, and surface curvature were modeled above longwall panels 7NW and 8NW using the Windows version of the SDPS subsidence package. The objective of the subsidence modeling was to quantify changes on a shift-by-shift basis so that the gas transmission line could be raised or lowered in response to the ground movement. The curvature and strain measurements were important because the hilly topography overlying the longwall panels. The affected sections of the transmission line were exposed and decoupled from the surrounding ground. There is a significant potential for the transmission line to slide downhill toward a valley, creating tensile strains at the adjacent crests. Although this problem was outside the scope of the subsidence study, engineers from the gas transmission company addressed this concern using the SDPS subsidence predictions.

Input parameters for SDPS were obtained from the bottom-of-seam elevations, mine projections, previous subsidence studies in the area, and core logs provided to AME by the coal company. These input parameters include:

- the percentage of hard rock (including sandstones and limestones) in the overburden (30%, average value from 13 core holes),
- the average mining height (6.20') taken in the longwall panels,
- an overburden thickness grid created from the difference between the surface topography and the top-of-seam elevations,
- the tangent of the influence angle (2.90 which corresponds to an influence angle of about 71 degrees, obtained from calibration runs using surveyed subsidence data from previous studies),
- the coefficient of horizontal strain (0.35) (the SDPS default value),
- the projected 7NW and 8NW longwall panel areas (developed

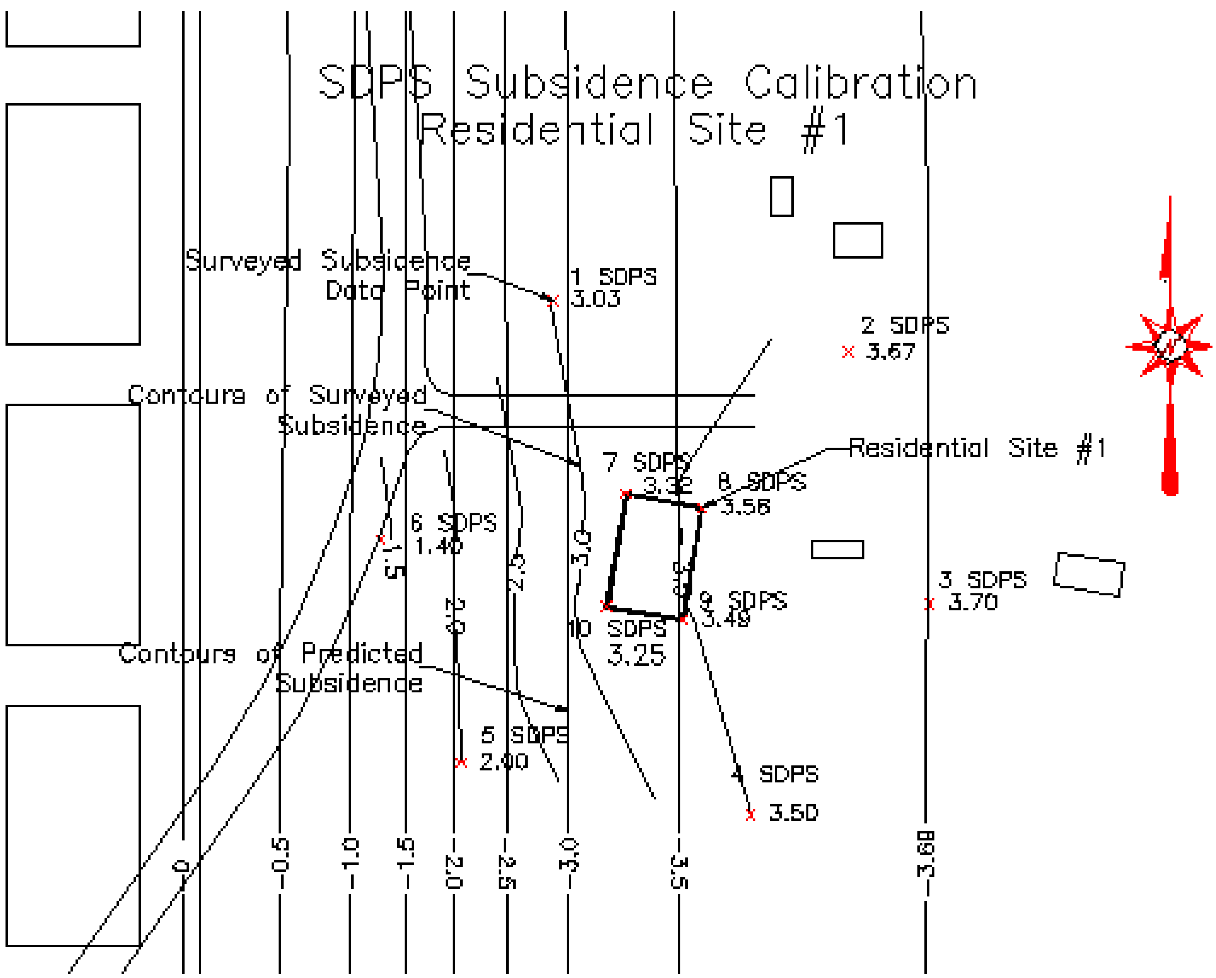

Figure 2. Calibration Results From Residential Site Number 1.

from company mine mapping),

- the edge effect (obtained from calibration runs), and
- the subsidence factor (obtained from calibration runs).

SDPS Modeling - Gas Transmission Line

The gas transmission line was stationed on ten (10') foot increments along the length of the pipeline. An arbitrary point was picked for station 0+00 at a location far enough to the West of Panel 8NW to ensure all areas of the pipeline affected by subsidence were covered in the model. Northing and Easting coordinate values tied to state plane coordinate system are listed for each station in the data sheets. A subsidence prediction point was placed at each ten (10') foot station and assigned an elevation to match the surface grid created for each seventy (70') foot increment of the projected daily longwall face advance and transformed into a 3D model to match the bottom of excavation elevations.

Using the seventy (70') foot longwall face advancement, the SDPS models were run to simulate subsidence data predicted upon daily face advance. Forty-six (46) SDPS models were evaluated to predict subsidence information along the gas transmission line on a daily basis as the pipeline was undermined. Each model generated information on the subsidence or vertical movement, horizontal displacement, angle of horizontal displacement, maximum soil strain, and angle of maximum soil strain for four hundred-four (404) individual prediction points along the gas transmission line. This subsidence information was then placed into a spreadsheet and graphs of ground movement and strain were generated for each model.

The graphs depict the maximum and minimum values occurring at each station along the centerline of the pipeline. An example of one of the graphs is shown in Figure 3. It should be understood that the maximum and minimum are end points for the subsidence activity. A given point on the pipeline is subjected to a continuous sequence of movement, frequently alternating between tensile and compressive strains. Horizontal displacement has a similar sequence of movement. As the longwall face approaches a specific point, the ground moves toward the mine void. Once underneath the point all movement is downward into the gob. As the face passes the point, the ground may move in the direction of the face dependent upon the location of the point relative to the longwall panel.

A maximum of 3.69 feet of subsidence occurs at those stations at the center of each panel and dissipates to zero for those stations at the panel edges. The gateroad separating the two panels is similarly an area of zero vertical movement. The maximum strain graph shows both tensile and compressive values for each station with the exception of stations between the panels and stations at the beginning of the 7NW panel. As the face advances, each station passes through a range of compressive or tensile strains dependent upon the location of the face relative to the station. The entire range of strain lies between the tensile and compressive maximum values. The area between the two longwall panels from station 15+80 to station 19+10 does not experience compressive strain since the movement is toward the longwall void and the area is supported by gateroad pillars. Similarly, the area at the beginning of the 7NW longwall panel from station 27+00 to 27+90 is limited to tensile strains. From 0+00 to 5+40 only tensile strains occur because of a combination of solid coal directly beneath these points and the "edge effect." The points at these stations do not experience the longwall face approaching and then departing as do the other stations. The graph shows a maximum tension strain of .021 feet/foot at station 13+60 and a maximum compressive strain of .029 feet/foot at station 27+10. It should be noted that all the strain values are soil strains and not necessarily the same magnitude of strain experienced by the gas pipeline. The friction and cohesion between the soil, rock bedding, and the pipeline determines the amount of soil strain transferred to the pipeline.

The history of subsidence induced soil strains and ground movement resulting from the mining of longwall panels 7NW and 8NW have been predicted at ten (10') foot intervals along the gas transmission line using SDPS. The gas transmission line was decoupled from the ground prior to mining panel 7NW. As this panel was mined, the gas transmission lne moved in response to the ground movement. No problems were encountered with the integrity of the line, which operated at normal pressure during the entire undermining. Panel 8NW was abandoned due to high in-seam and out-of-seam reject.

Conclusions

The results presented in this paper clearly demonstrate the ability of the SDPS package to be calibrated to accommodate regional subsidence characteristics provided that such data are available. Subsequently ground deformation indices including subsidence, horizontal strain and horizontal displacements can be calculated for various production stages to determine the dynamic subsidence effect and its potential impact to surface structures. The analysis described in this paper, for a typical case study, can be accomplished using current technology and its recommendations may prove invaluable for subsidence control.

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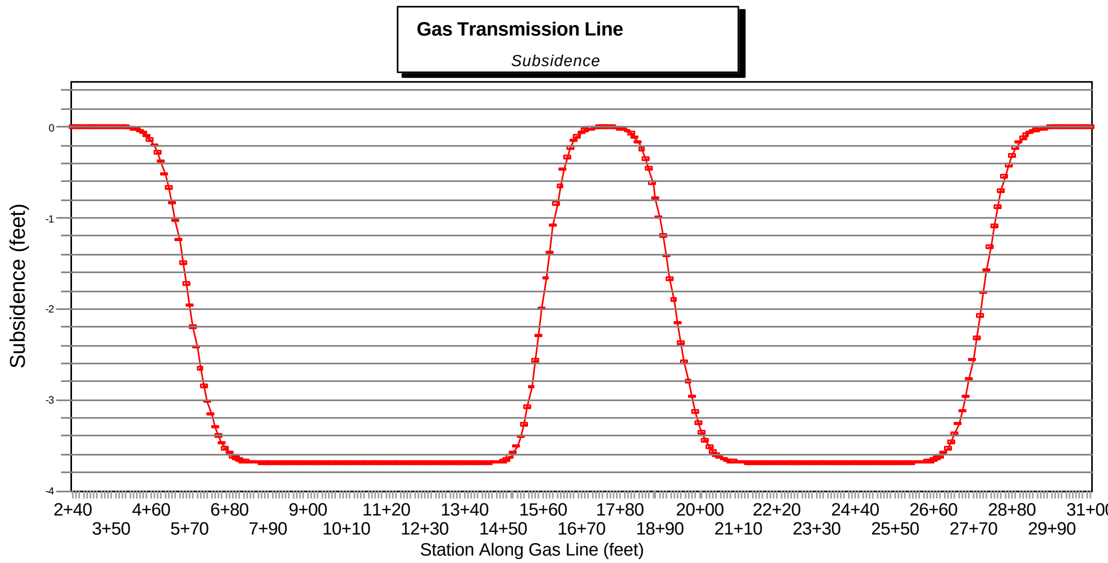

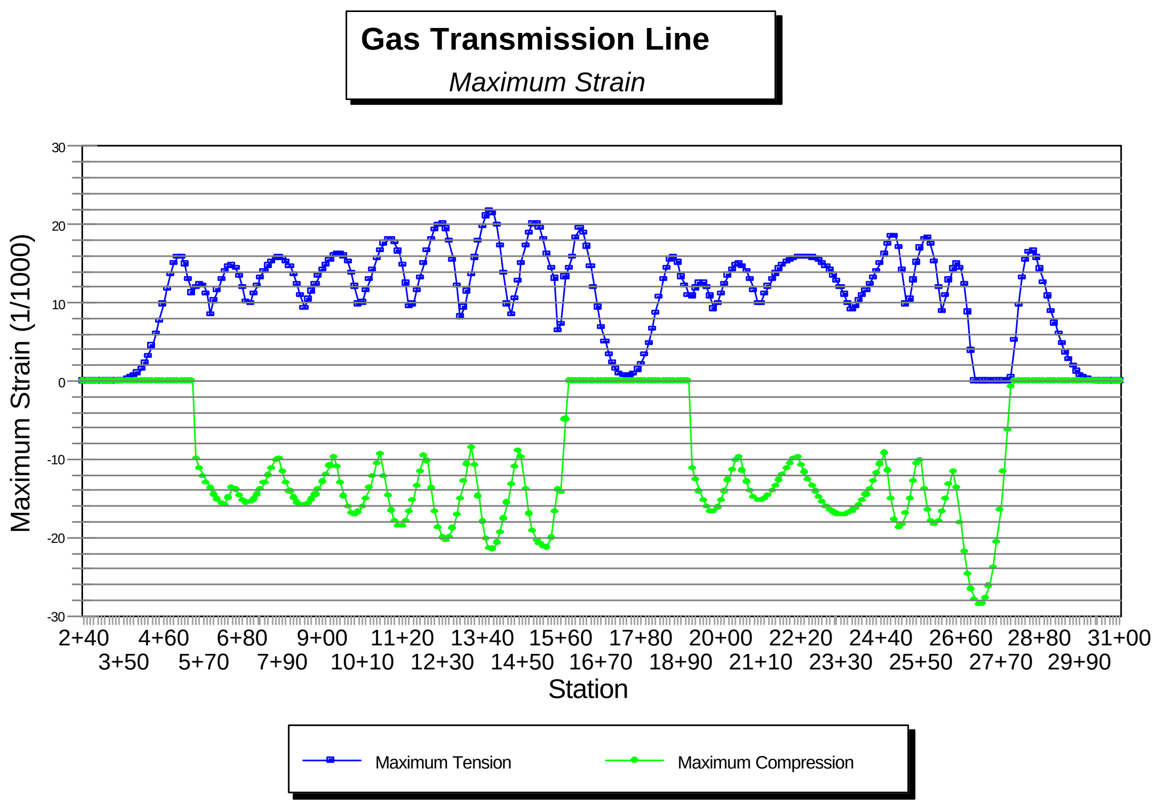

Figure 3. Maximum Subsidence and Maximum Strains Along Gas Transmission Line as Predicted Using SDPS.