Slope Stability monitoring in Open Pit and Underground mine by means of Radar Interferometry

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Abstract

This paper presents monitoring results of an open pit and underground mine obtained during several years, using X-band high-resolution images of TerraSAR-X satellite. This monitoring project began in 2008 and ground displacement evolution has been studied until 2012. Several Radar Interferometric techniques have been used in order to detect a huge range of displacement intensities, from millimetric to metric movements. A combination of phenomena caused by mine activities has been detected, showing a perfect temporal correlation with the mine evolution. This project has also been very useful for the control and analysis of a strong slope instability affecting the open pit, reaching displacements of more than 10 meters in some months.

Several vulnerable parts of the mine have been studied, taking into account the presence of infrastructures and other facilities. Two types of measurements have been performed based on the nature of points:

- Natural reflectors: Those natural points detected by the backscattering of the terrain, i.e. buildings, rocks, arid surface, etc. Measurement quality depends on the temporal changes of these areas.
- Artificial reflectors: Triedral structures, have been installed on certain areas of the mine, in order to ensure measurement points in areas with strong surface changes (what is known as temporal decorrelation) or with specific interest.

This paper demonstrates the capabilities of radar technology to generate complete ground deformation maps of an open pit mine, especially to follow and detect from very small to very large instabilities providing valuable information for risk and exploitation management.

1 Introduction

The coal mine analysed is situated in north-eastern Spain (Figure 1). It is a large-scale open-pit consisting of alternating lutites, sandstone, and seams of coal, distributed evenly over the four slopes that make up the open pit. The pit slopes are large, with a total height from between 100 m to 350 m. The mine’s benches are 10 m in height and the berms have a width of 5 to 6 m. Although coal is extracted by open-pit mining operations, underground operations are also performed in the southern slope to mine some of the existing seams of coal.
The coal deposit consists of very thick, highly irregular vertical and sub-vertical seams [1]. Of all of these, the Pastora Formation is that of greatest financial interest, as it is this formation that provides all of the coal production for the current mining centres. Operations currently focus on the western edge of the coalfield. The Pastora and Competidora seams are the thickest seams in the coalfield.

The Pastora seam (Santa Lucia group) runs for 1600 m in a primarily north-south direction, with varying dips, with values close to 30º. Its thickness varies from 7 to 40 m, and within the seam there are bands and wedges of varying thicknesses, shaped like lenses, of varying hardness and composition, ranging from soft slate to sandstone.

The area where mining operations are performed on the Competidora Seam runs some 1680 m in a majorly north-south direction with dips ranging from 60º to 80º. Its thickness varies from 2 to 25 m, with 14 m being the most usual thickness.

2 Radar data used

During the last four years a stack of TerraSAR-X images has been acquired over the mine area. These images have been programmed in the Stripmap mode of the satellite (descending orbit), which means an approximate spatial resolution of 3 metres on ground. Table 1 shows the list of all the SAR acquisitions divided into different colours that correspond to each yearly study, beginning from 2008-2009 and ending in 2012. It is important to remark that each study has been performed with images out from the winter period, when snow coverage degrades the signal quality backscattered to the satellite. In the case of this paper, results are focused on the last two years of the study (2011 and 2012).
Table 1  List of SAR images (TerraSAR-X satellite) during the last 4 years

<table>
<thead>
<tr>
<th>#</th>
<th>Date</th>
<th>Orbit</th>
<th>#</th>
<th>Date</th>
<th>Orbit</th>
<th>#</th>
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<td>15</td>
<td>18/11/2009</td>
<td>13469</td>
<td>29</td>
<td>07/08/2011</td>
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<td>14/02/2010</td>
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<td>30</td>
<td>09/09/2011</td>
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<tr>
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<td>17</td>
<td>08/03/2010</td>
<td>15139</td>
<td>31</td>
<td>12/10/2011</td>
<td>23990</td>
</tr>
<tr>
<td>4</td>
<td>21/12/2008</td>
<td>8626</td>
<td>18</td>
<td>10/04/2010</td>
<td>15640</td>
<td>32</td>
<td>14/11/2011</td>
<td>24491</td>
</tr>
<tr>
<td>5</td>
<td>01/01/2009</td>
<td>8793</td>
<td>19</td>
<td>13/05/2010</td>
<td>16141</td>
<td>33</td>
<td>17/12/2011</td>
<td>24992</td>
</tr>
<tr>
<td>6</td>
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<td>9294</td>
<td>20</td>
<td>15/06/2010</td>
<td>16642</td>
<td>34</td>
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<tr>
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<td>23</td>
<td>11/09/2010</td>
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<td>04/08/2012</td>
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</tr>
<tr>
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<td>17/06/2009</td>
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<td>06/09/2012</td>
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<td>13</td>
<td>24/09/2009</td>
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<td>02/06/2011</td>
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<td>14</td>
<td>16/10/2009</td>
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<td>28</td>
<td>05/07/2011</td>
<td>22487</td>
<td></td>
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</tr>
</tbody>
</table>

An example of amplitude SAR images is depicted in Figure 2. An orthophoto of the area of interest is compared with the SAR image obtained from combining the eight acquisitions from 2012. It is important to note the different bright levels that correspond to different backscattering intensity depending on the surface characteristics. The area under specific study is the East slope of the open pit mine, which is affected by medium (millimetric-centimetric) and strong (metric) displacements.
3 Radar methodologies

Displacements affecting mine slopes can range from some millimetres to several meters. These different behaviours must be studied using different technologies based on SAR data. A first classification of events can be done taking into account the displacement intensity, which implies different radar techniques for their correct measurement:

- **Millimetric and centimetric movements**: This kind of displacement is usually caused by underground activity or low-motion slope instability. These events can be measured using Persistent Scatterer Interferometry (PSI) techniques (Adam et al., 2009), like the Stable Point Network (SPN) methodology developed by Altamira Information (Arnaud et al., 2003). This technique uses the phase information from the radar signal in order to precisely detect the ground motion. Millimetric precision is obtained with SPN, and a maximum threshold of ground velocity can be measured depending on the number of SAR images and the temporal period of the study. Typically, this maximum velocity ranges from 15 to 30 cm/year in case of X-band satellites, like TerraSAR-X.

- **Metric movements**: Due to the limitations of PSI techniques regarding the maximum measurable velocity, Altamira Information developed another methodology to detect metric displacements for the mining industry. These very strong and sometimes fast movements can be found in mine slopes and represent a major problem for the mine safety, mainly in infrastructure and working areas.

As presented in this paper, combination of both methodologies allows obtaining a complete displacement map of the area of interest, no matter the movement intensity.

Furthermore two different types of measurement points have been used on the monitoring of this mine. These points can be classified as natural and artificial reflectors:
• **Natural reflectors:** These are the measurable points of the surface under study. They must not change their surface characteristics during the temporal period of monitoring. These natural reflectors can be buildings, infrastructures, bare soils, low-vegetation areas, etc. Not all the points in the image can be classified as natural reflectors, and therefore only a part of the image pixels can be measured by means of radar interferometry.

• **Artificial reflectors:** Trihedral structures that can be installed on surface, in order to ensure measurable points where natural reflector density is very low. Artificial reflectors do not need any additional maintenance, and power supply is not required. Figure 3 shows an example of natural points and artificial reflectors.

![Figure 3](image)

Figure 3  Natural (left) and Artificial Reflectors (right) installed in the mine slope

### 4  Radar results

Two different radar techniques have been used for the monitoring of slope stability, with the objective of detecting several scales of ground movement, from millimetric to metric. This is a very important point, since movements found in a mining area can present different behaviours with diverse displacement intensity. Obtained results are presented in the following sections.

#### 4.1  Stable Point Network (SPN)

This methodology allows detecting millimetric and centimetric displacements with high accuracy. This advanced interferometric technique developed by Altamira Information uses a stack of SAR images (typically 15-30) to measure ground deformations with millimetric precision (Duro et al., 2003). During the processing, the ground scatterers not affected by temporal decorrelation are identified; these are called persistent scatterers or stable points. They are natural objects over the ground surface that give a very good reflection to the satellite throughout the entire stack of images. These points present a reduced level of noise, which allows very reliable measurements. Furthermore, the atmospheric effects are estimated and compensated during the processing to derive highly accurate elevation and displacement values for each stable point. The highly precise error compensation allows to generate time series charts that provide a visualisation of the evolution of the displacement of each stable point. Urban, semi-urban or rural areas can be studied in great detail, both in terms of high spatial resolution and the historical variation of the displacement over long time periods.
Figure 4 shows displacement maps for two different years (non-winter months), 2011 and 2012. Differences on ground deformation can be observed, mainly in the Southern part of the slope, where velocity decreases during 2012. Another important issue is the distribution of measurement points, depending on surface changes in the open pit. For example, lack of points is more present during 2011, when a higher surface activity has been reported.

On the other hand, a large area without detected points is clearly visible in the center of the slope. This is due to extreme displacements, more than 5 meters, presented in the next section. These displacements cannot be measured by means of interferometric phase due to aliasing.

Ground deformation maps of Figure 4 correspond to natural reflectors measurements. Nevertheless, additional information can be retrieved using artificial reflectors, as it is shown in Figure 5. In this case, six aluminium trihedral reflectors have been installed in the studied slope, covering it from North to South. The three northern reflectors are located in a stable zone, as the natural reflector map shows. Nevertheless, the other three are installed on a deformation area, and their time series confirm the same movement pattern obtained from natural reflectors. This is an interesting study that confirms the functionality of both methodologies, natural and artificial reflectors. The advantage of artificial points is that only 3 or 4 SAR images are necessary for a first processing, while a larger dataset (typically more than 15 acquisitions) is recommended for SPN on natural reflectors.
4.2 NCT technique

This technique has been developed to monitor large ground displacements, in the order of meters. This is necessary in order to measure those movements larger than the critical value of the SPN methodology, which depending on the number of SAR images and the temporal span can be about 20-30 cm/year. Results of this processing are presented in Figure 6, where the strong intensity (more than six meters) and affected area are clearly visible. Nevertheless, the obtained map for 2012 presents a lower displacement compared with 2011.

In order to show the complementarity of SPN and NCT maps, Figure 7 shows the combination of both results. Note that the location of SPN natural reflectors is restricted to millimetric-centimetric displacements, while the NCT map is restricted to the metric movements, generating together a complete deformation map of the area of interest.
Comparison with other measurements and evaluation

During the same temporal period of the radar study, a conventional analysis of the eastern slope has been carried out, with the scope to test if radar measurements provide high-quality information of the deformation phenomena.
Analysis of the different types of materials was performed exhaustively along the different benches of the mine. We thus determined the characteristics and distribution of the lithology that make up the mine’s slopes. Each of the identified types of materials is found in very specific areas in the mine. Most of the open pit consists of lutites, sandstones and coal seams.

In addition, a study of slope degradation has been carried out, analysing the degree to which these have been altered. Significant fractures, landslides, and subsidence have been observed. To a lesser degree multiple signs of failure have been detected, indicating fractured layers, dislocated blocks and open joints. All of this evidence has been taken into account to determine the resistant properties of the rock mass.

The eastern slope and the south-eastern slope are the most affected areas. In these slopes a considerable amount of evidence of instability has been detected, such as fractured blocks, overturned berms, and landslides. Figure 8 shows the relevant degree of alteration.

![Figure 8 Degradation in an area of the eastern slope](image)

In addition, along the eastern slope in the Santa Lucía open pit, there is a significantly large fault running close to the Competidora seam. This seam is mined via underground works operations. Figure 9 shows the location of the fault area. We also have to add examples of subsidence in the head to the detected strains. These may be a result of this fault interacting with the nearby underground mining operations. Therefore, observations demonstrate that the detected displacement magnitude by means of radar technology is coherent.

![Figure 9 Eastern slope fault area](image)
To determine the stress and strain properties of the materials in the mine, several field tests were performed. Some tests were performed using hydraulic cylinders in each of the areas where different materials are found. The aim of these series of tests was to determine the modulus of elasticity, the Poisson’s ratio, the cohesion and the angle of friction of the materials. The equipment and the measurement method used have been developed and patented by the University of Oviedo’s Geotechnical Engineering Research Group (GIT), taking into consideration the recommendations made by the International Society for Rock Mechanics. It basically consists of applying pressure to the ground using a metallic plate with a circular cross-section and a known diameter, and then measuring the resulting strain.

The mean values for properties obtained in the tests are shown in Table 2.

Table 2  Properties of the model's materials

<table>
<thead>
<tr>
<th>Material</th>
<th>E (Pa)</th>
<th>ν</th>
<th>c (MPa)</th>
<th>ϕ(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstones with bands of lutites</td>
<td>5.5e9</td>
<td>0.30</td>
<td>1.1e6</td>
<td>29</td>
</tr>
<tr>
<td>Lutites</td>
<td>6.1e8</td>
<td>0.40</td>
<td>5e5</td>
<td>24</td>
</tr>
<tr>
<td>Coal</td>
<td>3.0e8</td>
<td>0.40</td>
<td>4e5</td>
<td>24</td>
</tr>
<tr>
<td>Sandstones and lutites</td>
<td>3.5e9</td>
<td>0.40</td>
<td>9e5</td>
<td>27</td>
</tr>
</tbody>
</table>

In order to determine whether the signs of instability observed in the southern slope are a result of interaction between the underground mining operations and their proximity to the fault, a two-dimensional numerical model was generated and calculated using the FLAC v6.0 application. This model represents a longitudinal section parallel to the direction of the analysed slope, as can been seen in figure 10. The different materials present in the rock mass have been considered in the model, plus their distribution with respect to each other. The presence of a normal fault that crosses the slope has also been taken into consideration. Figure 11 shows the diagram for the analysed model.

The model has been divided into several calculation phases to simulate as closely as possible the operations that are in reality performed. A total of eight phases have been defined:

- Phase 1: Initial stress in the rock mass without any part of the rock mass being subject to mining operations.
- Phases 2, 3 and 4: Successive mining of three small coal seams located at different levels in an area located to the left of the fault.
- Phases 5, 6, 7 and 8: Sub-level caving of four different levels in the Competidora seam, with a 30 m high vault support structure and leaving intermediate 70 m rock masses.

The results obtained from the modelling of phase 1 do not indicate the existence of plasticized areas. As such, before mining operations began in the eastern slope no damage was noticeable. In phase 2, the mining of a first seam of coal located to the left of the fault was modelled. In this case the plasticised area only covers the area where mining operations occur as can be seen in Figure 12, where vertical displacements in the seam are represented. Subsidence has a maximum value that does not exceed 50 cm. The maximum horizontal displacements are 20 cm long and close the pit mine.

![Figure 12 Vertical displacements in phase 2](image)

During the modelling and simulation process for this phase, two control points were placed on either side of the fault, as can be seen in Figure 13. We can thus study the influence that this phase of mining operations has on the immediate surroundings of the fault, by monitoring the evolution of the vertical displacement of these points.

![Figure 13 Displacement at control points](image)

Figure 14 shows a diagram with the evolution of the vertical displacement of the control points. The material located to the right of the fault (control point 2) experiences subsidence of 5 cm, and in the area to the left (control point 1) positive displacement was observed (swelling) of only 5 mm. These values are totally insignificant in the context of a large-scale fault such as that simulated in this model.
In phases 3 and 4 another two seams were subject to mining operations in the area to the left of the fault, at different levels and distances from the fault.

The results obtained again show that plastification and displacements are restricted to the immediate environment of the seams subject to mining operations. The fault is, however, now slightly affected, as the seams of phases 3 and 4 are closer to the fault. The vertical and horizontal displacements tend to close the pit mine.

In this phase, negative vertical displacements (subsidence) of approximately 1 m at both control points (to the left and right of the fault) were recorded. It is clear that the magnitude of the displacements around the fault has undergone a notable increase with the mining of these seams. In any case, these phenomena do not affect the entire slope, but are still highly localised.

Phase 5 corresponds to the commencement of sub-level caving of the Competidora seam, with a mine vault support structure height of 30 m, as shown in Figure 15. In this phase, the largest displacements in the model are located on the ceiling of the area where sub-level caving operations take place, which is the area that is most deformed in order to close the pit mine. Thus, subsidence in excess of 25 m is observed in this area, due, logically, to the mining process.

In order to more reliably analyse the influence of this new phase of sub-level caving on the fault area, the displacements for control points 1 and 2 were reset to zero. Hence, the information recorded at the control points during the simulation is a result, solely, of the mining operations to which the Competidora seam is subjected during this phase. These are very small in size, not exceeding 3 cm. As such, sub-level caving in this first level of the Competidora seam (phase 5) only affects the area of the slope close to these operations. No significant strains exist near to the fault.

Phase 6 involves a simulation of sub-level caving of the second level of the Competidora seam to a depth of 225 m. Horizontal displacement reaches values of up to 6 m whilst the maximum vertical displacements consist of subsidence phenomena of up to 30 m, practically the same height as the mine vault support structure. Figure 16 shows the vertical displacements for this phase.
In addition, the plasticity of the model after this phase shows how the areas near to the fold hinge of the Competidora seam are plasticized by the cutting forces.

This phase of sub-level caving also affects the area of the control points, especially point 2, due to its closeness to the area where these operations take place. At this point the vertical displacement changes from only 3 cm in the previous phase to almost 1.50 m in this phase. At control point 1 there is considerably less increase in displacement, changing from 2 to 10 cm.

The next phase of sub-level caving (phase 7) was located directly in the fold hinge of the Competidora seam, in the area of the seam closest to the fault, at a depth of 375 m (Figure 17). Both the horizontal and vertical displacements of the model and plasticity follow the trend observed in previous phases. The maximum displacements are located in the ceiling of the area where sub-level caving operations took place, with values greater than 30 m for vertical movements and 5 m for horizontal displacements. This new phase, located very close to the fault zone, causes significant subsidence in the right-hand section of the fault area, as can be seen by the value of 10 m recorded at control point 2 (see Figure 18). A displacement of this magnitude also causes surface-level subsidence to occur.

The last study phase (phase 8) consisted in the simulation of sub-level caving of the Competidora seam below the fault fold hinge, at a depth of 475 m. With the plasticity obtained we can see how plastification now affects all of the seam and the surrounding area. The most important damage, due to cutting forces, is found near to the surface, in the area located to the right of the fault (Figure 19).
On the other hand, the movement trend witnessed in this phase is practically identical to that seen in the previous sub-level caving phases. Horizontal movement values are close to 5 m whilst vertical displacements reach values of 30 m in the ceiling. Displacements of 50 m were registered in the areas that had been subject to sub-level caving in previous phases, as can be seen in Figure 20. This is due, logically, to the continuous strain to which the materials in previously mined areas continue to be subjected.

The increase in subsidence at control point 2 recorded in this phase was 3 m in comparison to the previous phase, giving a value of 13 m. The movement at point 1 continues to be extremely reduced (15 cm).

These results are perfectly consistent with those obtained with radar technology in both parameters:

2. Location of movements: All metric displacements are located in the same side of the fault, and the minor movements (milimetric or centimetric) in the other side.

6 Conclusions

The application of advanced satellite interferometric techniques shows to be a perfect tool to understand, quantify and map slope instabilities. InSAR measurements provide support in the evaluation of the existing subsidence mechanisms and are effective risk management tools used in worldwide mines to activate mitigation measures when required.

This paper shows an approach to understand and better interpret the measured InSAR motions in an open pit and underground mine by using natural and artificial reflectors and by applying SPN and NCT technologies. All range of measurements have been covered in order to assure a comprehensive approach.

This paper also goes a step further by showing the calibration of InSAR results with ground data and the modelling work developed by the University of Oviedo, Spain.

The discussed results demonstrate the suitability and the potentiality of InSAR technology to complement and under certain conditions even supplement other in-situ surveying techniques for a better characterisation and understanding of the mine induced ground deformations.

The presented case study has been performed using archive data from a high resolution satellite but with limited quantity of images, nevertheless the results already show the extreme potentiality of the technology.

Advanced InSAR processing techniques for mining demonstrate several distinctive parameters that define this remote sensing methodology as a very promising, effective and cost saving surveying technique, the most important ones being:
High density of measurements points that allows to precisely set the boundaries of the ground deformation and to map the different shapes and magnitudes affecting each zone (thousands of points in Km2).

- High precision of measurements (1 to 2 mm) that places SPN interferometry as one of the most precise surveying technologies.
- Pixel size (3 m) allowing an excellent sampling of the results.

Nowadays, with the current radar satellite constellations it is possible to program an intense data acquisition that will assure gathering data with maximum precision and accuracy.

For the mining operator, the use of these techniques, together with the application of geotechnical knowledge provided by the University of Oviedo is enabling to better understand the behaviour of terrain which is simultaneously affected by underground and external excavations, proving as an essential tool for the geometric design of future mining extensions.

Acknowledgements

Emilio Amor of Hullera Vasca Leonesa (HVL) assisted in the preparation of plots in this paper and provided editorial assistance on this paper; his generous assistance is gratefully acknowledged.

References

