Residual subsidence analysis after the end of coalmine work. Example from Lorraine colliery, France

Marwan Al Heib, M. Nicolas, J.F. Noirel, Francis Wojtkowiak

RESIDUAL SUBSIDENCE ANALYSIS AFTER THE END OF COALMINE WORKEXAMPLE FROM LORRAINE COLLIERY, FRANCE

Al Heib M.[(1)], Nicolas M.[(2)]. and Noirel[(2)] J.F., Wojtkowiak F.

[1] INERIS LAEGO - Ecole Nationale Supérieure des Mines de Nancy, Parc de Saurupt – F 54042 Nancy Cedex, France. vincent.renaud@ineris.fr

[2] Charbonnage de France, 2, rue de Metz, 57802 Freyming-Merlebach,

ABSTRACT : *This paper describes the residual movements associated with the deep coalmines. The studied case relates to works located into Lorraine coal basin. The paper is divided into two sections. The first one describes subsidence phenomena, especially the residual phase in terms of amplitude, duration and localization. The second one focus on Morsbach case: the total and residual subsidence measurements will be analyzed and compared to the state of the art as well as the currant knowledge. The results of the analysis show that the duration of residual movements does not exceed 24 months and their amplitude is about 5% of total subsidence. We analyze also the declarations of the mining damage during and after the mining period. Damages occur, after this period are probably due to late observations.*

KEY WORDS: *coalmines, residual subsidence, mining damage, subsidence measurements*.

Résumé : Cet article décrit les mouvements résiduels associés à l'exploitation des mines de charbon à grande profondeur. Le cas traité concerne le secteur de Morsbach, influencé par une exploitation de charbon en Lorraine. L'article se décompose en deux parties : la première partie décrit le phénomène d'affaissement, et particulièrement la phase résiduelle de l'affaissement (amplitude, durée, localisation), la deuxième partie est consacrée au cas de Morsbach, pour lequel nous analyserons les mesures d'affaissement (totales et résiduelles) par rapport à l'état de la connaissance. Les résultats de l'analyse montrent que la durée de l'affaissement résiduel ne dépasse pas 24 mois et que son amplitude est de l'ordre de 5% de l'affaissement total. Nous avons également analysé les déclarations des dommages et des dégâts miniers pendant et après l'exploitation. Les dommages observés après l'arrêt des travaux sont probablement dus à des observations tardives.

MOTS CLES : *mines de charbon, mesures d'affaissement résiduel, dégâts miniers*.

1. Introduction and objectives

The last panel of Lorraine French coalmines has been mined in 2004. The subsidence prediction during the mining period was completely controlled. Today, we focus on the residual subsidence phase. The problem is the existence of other movements whose amplitudes are comparables to residual subsidence. In this paper, we will discuss various processes can led to ground movements comparable to residual mining subsidence. The analysis of a case studies make it possible to improve knowledge and city management of zones where risks of residual subsidence can occur. One of them is the Morsbach city (57), well documented, from Lorraine colliery. It enables us to check the classical rules describing the evolution of mining subsidence during and after the mining period. This case also offers an interesting opportunity because the data related to subsidence measurements and mining works are complete. We will examine the final subsidence under the city of Morsbach (1996) and consequences on the existing and future buildings of the sector.

2. Mining Subsidence: Theoretical aspects and definitions

The underground excavations induce the bending and the deconsolidation of the overlying strata. The induced displacements are transmitted on the surface and form a subsidence trough (figure 1). This subsidence trough extends on a surface above the exploited area; its volume remains less than the extracted one due to the bulking effect. Figure 1 indicates schematically the geometry of the subsidence profile. The characteristics of the subsidence trough are: influence angles (or limit angle) and maximum subsidence amplitude Am.

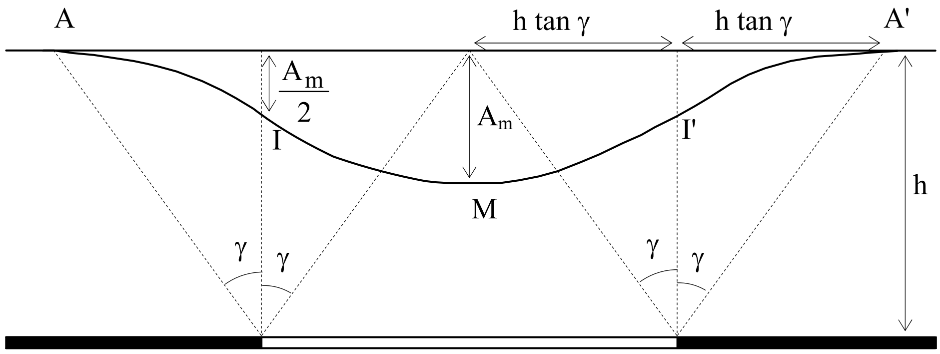


Figure 1: Theoretical subsidence trough above a single panel at critical width in horizontal seam (after Proust, 1964)

The movement at the surface has a vertical component, the subsidence itself, and a horizontal component. The displacement is systematically oriented towards the centre of the trough. Horizontal displacements generate differential displacements and those induce horizontal strain in compression and extension (figure 2). The damages occurring on infrastructures are mainly induced by the horizontal strain, the zones in tension being, in general, more unfavourable than those in compression.

When the ratio “width of the zone/depth” is greater than 1.4, for an influence angle of 35° (typical value of Lorraine coalmines), the configuration is said supercritical and the subsidence amplitude is maximum. A sub-critical surface requires a correction of the subsidence value, and maximum of tilt and strain values. The correction depends on the geometry of the zone. The maximum tilt (P_{max}) is calculated using the following empirical relation: $P_{max} = \beta$ Am/H (Am: maximum subsidence, b: depends on the nature of strata). The maximum horizontal strain ε_{max} is calculated using the following empirical relation: $\varepsilon_{max} = \alpha$ Am/H. In the context of the Lorraine coal basin, the experience feedback highlights that β is considered equal to 3 and α is generally taken equal to 0.75.

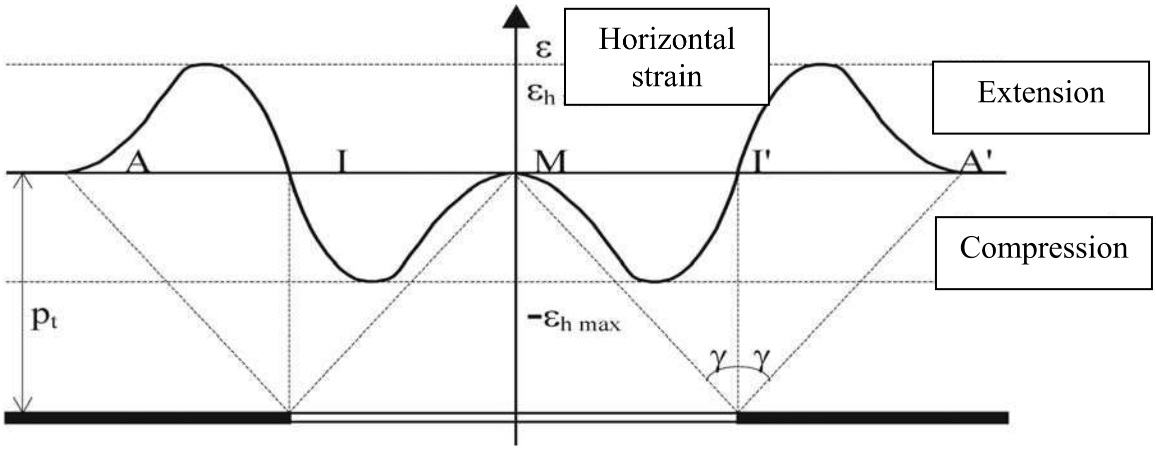


Figure 2: Theoretical horizontal strain variations above a supercritical single panel (Proust, 1964)

3. Phases of mining subsidence

The final subsidence can be divided into three phases as illustrated in figure 3, (Wojtkowiak, 1997). Phase I known as initial subsidence, corresponds to the period when the face of extraction penetrates the cone of influence. This cone is defined by the influence angle and the depth of the considered point, until passing to the vertical of this one. This phase is generally associated to 10 to 15 % of final subsidence. Phase II known as principal or accelerated subsidence corresponds to the period when the face of extraction moves away from the vertical of the point, until it leaves the cone of influence of this point. In the United-Kingdom coalmine, 97 % of final subsidence is reached at this stage. From the bibliography, the corresponding value of subsidence varies between 80 to 90 % of Am.

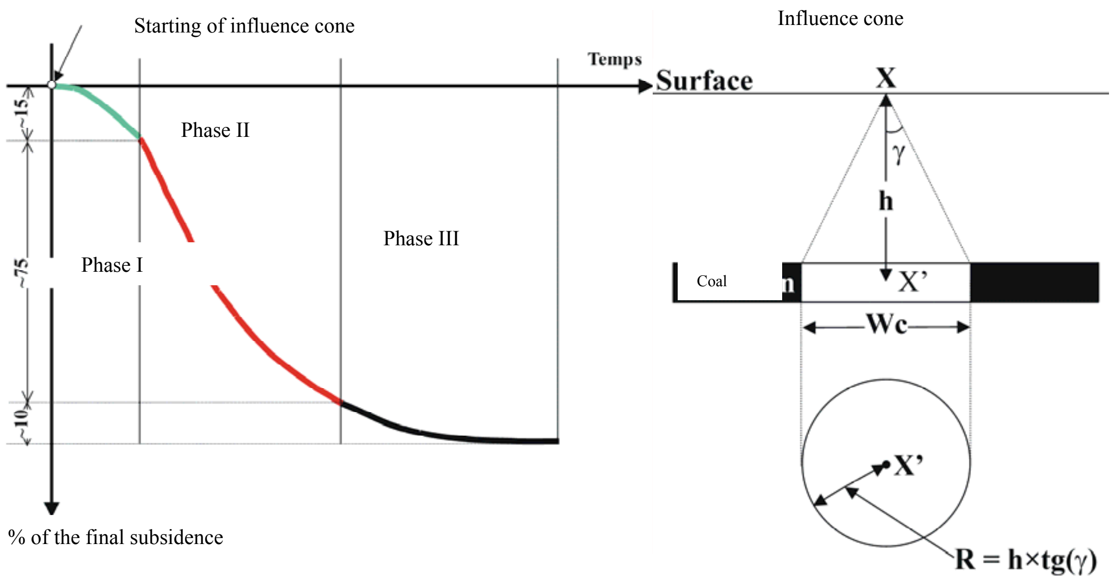


Figure 3: (a) Typical evolution of a subsidence profile with time; (b) cone of influence of a point located on the surface

Phase III, known as residual subsidence (also named differed or delayed subsidence) is constitutes the final phase of subsidence. It continues after the extraction phase or when the front of the face is out of the area that influences completely the considered point. Residual subsidence represents only some fraction of the total subsidence. After this last phase, subsidence is supposed finished and surface is stabilized.

4. Mining Damage Classification

Subsidence can induce damages on buildings and infrastructures. The damage severity depends both on the characteristics of the subsidence trough and the nature of the structures. The values presented in table 1-a classify the damage on structures in five categories. These values are determined from many back-analysis of many cases for ordinary buildings. Deck et *al*. (2003) after analysing various classifications available in the international bibliography propose three levels of damage scale. Table 1-b specifies the definition of each of these three classes of damages or degradations. Deck, (2002) has checked that this table is well correlated with the values of deformation thresholds given in table 1-a.

Damage classes	Horizontal strain (mm/m)	Tilt (‰)	Radius of curvature (km)
Very slight	$\varepsilon<0,5$	<2,5	>50
Slight	$0,5< \varepsilon <1$	<5	>20
Appreciable	$1< \varepsilon <2$	<10	>11
Severe	$2< \varepsilon <3$	<15	>8
Very severe	$\varepsilon>3$	>15	<6

Table 1-a: Scale of damage

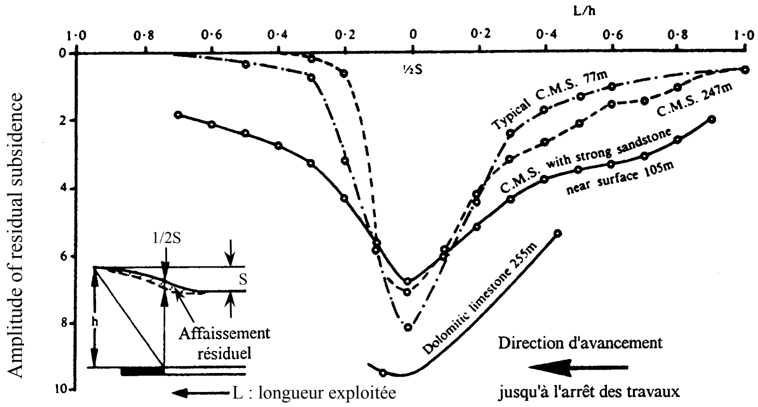
Classification of degradations	Description
Architectural	Low-size cracks in the plasters, wedging of the doors and the windows.
Functional	Instability of structural elements, blocking of doors and windows.
Structural	Sever degradation or collapse of the principal structural elements. Possibility of rupture of certain parts. Partial or total rebuilding is necessary. Major risks for the residing.

Table 1-b: Classification of scale of damages on the surface structures proposed by Deck et *al*., 2003

5. Residual subsidence

5.1. Amplitude and shape of residual subsidence

The amplitude of residual subsidence is generally about 1 to 10% of final subsidence (figure 3). This value is largely allowed by the whole French and foreign authors. The amplitude depends on many factors: thickness of the mined seam, depth, backfilling and goaf methods as shown in figure 5, the amplitude of residual subsidence is maximum in the vicinity of the inflection point of the subsidence trough. On both sides of this point, the amplitude of residual subsidence decreases significantly. Generally, residual subsidence decreases with the mine depth. One can highlight that, during the last two or three years of residual subsidence phase, that the amplitude of subsidence is negligible. The settling speed is decreasing over this duration. A great part of residual subsidence is given at the end of the first year (40 to 90 %), sometime before, (80 % after one month in a USA mine). In the Nord and Pas-de-Calais collieries, in France, residual subsidence does not exceed 5 mm per year after 18 months and 2 mm per year after 26 months in most cases.



S : subsidence ; L : length of long-wall ; h : depth of underground excavation

Figure 5: Residual subsidence for various coverings according ratio length exploited/depth (after NCB, 1975).

5.2. Duration of residual subsidence

Table 2 presents bibliographical data related to the duration and amplitude of the residual subsidence phase. We specified for each case the treatment method (goaf, backfilling) and the nature of strata. The duration of the residual subsidence phase is about 12 to 18 months, but this duration is often less long, i.e. about 3 to 4 months when the exploitation is carried out in an already disturbed zone (several seams, goaf...). There are some isolated cases resulting from geological contexts and/or particular exploitation, for these cases, the duration of residual subsidence can appreciably be raised and spread out over one period of 4 to 6 years.

Cases	Mining conditions	Residual subsidence
U.K. (Many basins)	Long-wall method and plastic layers	Less than 12 months ; 5-6 % of the total subsidence
UK (Durham Coalfield)	Tow mines with high resistance strata	1) 8 % of total subsidence after 4 years, and 9 % after 6 years. 2) 6.8 % of total subsidence after 4 years
West Germany	Many mines using long-wall method	5 years, with 75 % from the first year
Australia	Long-wall with caving method	3 to 7 months
India	Long-wall in virgin ground	10 months to 15 month for 10 to 30 % of total subsidence
	Long-wall method - in already extracted zones.	2 to 4 months; 5 to 10 % of total subsidence
USA	Long-walls method	10 % of total subsidence 1 month and 12 % after 17 months
France : Nord-Pas-de-Calais Albi - Carmaux	Plastic strata ; in already extracted zones.	99 % of total subsidence after 3 to 4 years
France : Provence, Lorraine And Blanzy	Resistant strata ; in already extracted zones	2 to 3 years

Table 2: Duration and amplitude of residual subsidence phase (after Aissaoui, 1999)

5.3. Consequences of residual subsidence on structures and infrastructures

Residual subsidence does not affect the surface constructions because the residual horizontal strains, which are more prejudicial, are practically small. One does not have specific study undertaken on the damage that mining works can induce during residual phase. One can however roughly estimate the horizontal strain and the tilt starting from relations established for the active phase. Maximum residual subsidence reaches only a small proportion of maximum subsidence (10%) in active phase. The residual maximum strain and tilt result from those in active phase in the same proportion. Since the horizontal strains reach in active phase, 0.1 to 3 mm/m (more rarely higher values), the order of magnitude of the additional horizontal strain, will be 10^{-2} to 10^{-1} mm/m in residual phase.

6. Other causes of ground movements

Other types of phenomena can induce movements of the same order of magnitude as residual mining subsidence (the pumping of ground water, compaction of soil, seasonal climatic variations or exceptional weather conditions of long duration, etc). These phenomena exist in mining zones like everywhere else. It appear to be very difficult to distinguish between what result from mining residual subsidence and what is ascribable to other natural causes.

As an example the natural variations of soil water content induces vertical displacements of the surface (Holzer and Pampeyan, 1981). The amplitude is equal to residual subsidence, and often in proportions much more important when man causes a major reduction in the piezometric level. The cases of Mexico City (Morales et *al*., 1991), and Fremont Valley in California are well-known examples.

Ground movements may also result of the hydrocarbon exploitation. They are very similar to those related to mining (Bau et *al*., 1999). The main difference comes from the great extension of the subsidence (10^2 to 10^4 km^2). In fact, due to depth and extension of the extracted hydrocarbons area, the hydrocarbons subsidence is comparable to a whole coalfield. Subsidence above the fields of hydrocarbon extraction develops a residual phase, during which the fluids move in-depth until finding a state of equilibrium.

The compaction of the soil depends on the water content variation that can be related on pumping, the climatic change, the increase in the stresses, etc. The order of magnitude of compressing can be similar with that of residual subsidence of mining origin.

7. Subsidence analysis of the eastern sector under Morsbach district

7.1. Presentation of study sector

The exploitation of the Marienau sector - commune of Morsbach started in 1970, used initially the method of the backfilling long-wall, when, later used the long caving faces method. The last panel was exploited at 1000 m depth. All seams belong to the upper bright burning coal (beam of Laudrefang). The field of Marienau is limited by the anticline Simon, the synclinal of Marienau and the fault of Fockloch. The thickness of the sandstone bed, above the carboniferous beam, is about 250 m. The least deep and oldest panels are in the east of the sector. The exploitation developed towards the west while deepening. The depth of the exploited panels lies between 470 m and 1070 m. The dip of the seams varies from 10° in the east of the sector, to 30° in the west of the sector. The total of 49 panels have been extracted from 13 seams with a variable thickness ranging from 1 to 3 m. The average thickness is 2.1 m. At the surface, above the exploitation, there are a forest and few structures. On the other hand, west of the highway, one can note the presence of several cities and principal roads.

7.2. Analysis of subsidence measurements

Charbonnages de France performed regular subsidence measurements before, during and after the exploitation. The levelling loop contains significant number of points. The levelling started in 1961, has been carried out by the services of Charbonnages de France. The final subsidence of studied sector has a dissymmetrical form, resulting from the geometry and number of exploited seams, which are more numerous in the east. The maximum amplitude of subsidence is 11.74 m, in the east of the sector. The curves of iso-subsidence are tight side, in the area corresponding to the forests (figure 6). The maximum tilt Pmax of the ground calculated from the curves of iso-subsidence is equal to 10% (this tilt is different from the one measured on existing buildings). The tilt does not exceed 2% in the urban zone of the Morsbach city. Figure 6 presents the location of a section going from the centre of the subsidence trough to outside the zone of influence.

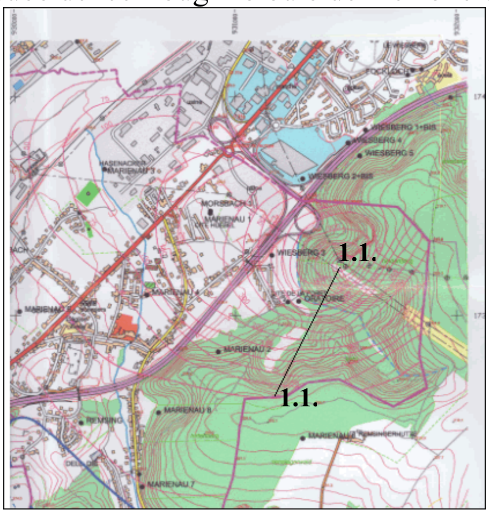


Figure 6: Final subsidence and location of cut A-B

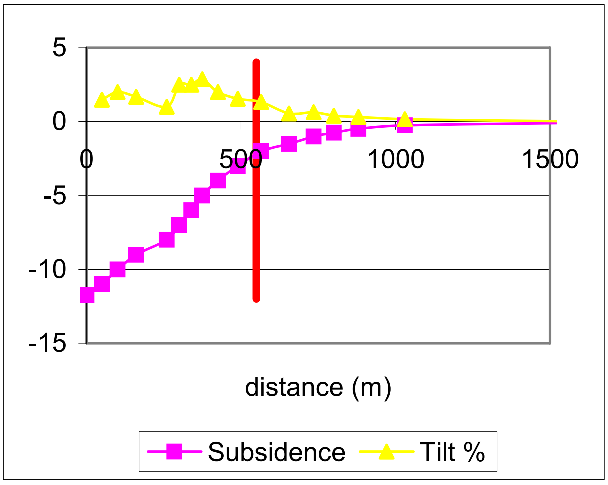


Figure 7: Subsidence (m) and tilt of Profile A-B

The figure 7 shows subsidence and tilt profiles. The angles of influence are difficult to determine due to the complex geometry of underground excavations and the surface topography. The angle of influence in flat seam equals 35° (without dip). In the case of an inclined seam, there are two angles: an upstream angle equal to 35° less the dip of the seam and a downstream angle equal to 35° plus the dip of the seam. For studied example, we calculated, using subsidence measurements, downstream angle (south-eastern) equal to 49°.

7.3. Measurements and prevision comparison

The cumulated average thickness of the 7 exploited seams at the centre of the subsidence trough is equal to 15 m. The surface exploited in each seam is supercritical. The maximum subsidence (Am) predicted by the following expression: $Amax = w * f1 * f2 * g$

- W: height of opening, - f1 and f2 empirical factors where f1 depends on the mode of treatment of the extraction area. It equals, for the Lorraine exploitations: 0.1 for a hydraulic stowing; 0.5 for a pneumatic stowing and 0.9 for caving. The depth factor f2 is equal to 1 for depths ranging up to 500 to 600 m and 0.8 for depths greater than 800 m (for the French coalmines). g: factor depends on the geometry of excavation of sub-critical panels. Maximum calculated subsidence, for a coefficient f1 ranging between 0.8 and 0.9, to take into account of the presence of certain backfilled panels, is between 12.7 m and 13.5 m. The forecast of subsidence by the method described above is close to the subsidence measured at the centre of the trough (11.75 m). The maximum tilt calculated according to the empirical relation (cf § 2) is equal to 4.5 %. The measured maximum tilt differs from the theoretical calculation of the maximum tilt. This difference is probably due to the dissymmetrical shape of the subsidence trough. The urban zone of the Morsbach city is in the zone where the tilt is less than 2%.

7.4. Characteristics of residual subsidence

The closure of the exploitation of the Marienau sector under the Morsbach city took place in 1996. The depth of the last panel is 1000 m. It is considered that the phase of residual subsidence started from this date. Subsidence measured in 1996 was 35 cm. On this date the subsidence was mainly affected by the exploitation of the last active panel. The subsidence measured in 1997 was only 20 cm, in 1998 the residual subsidence is null because no measurable movement has been detected. The cumulated value of residual subsidence thus lies between 20 and 55 cm. The period of stabilization of subsidence is less than two years. The results of these observations, in Lorraine coal basin, are conforming to the data resulting from the bibliography. Consequently, this period is also lower than 5 years, maximum period of stabilization noted in other basins. The location of maximum residual subsidence is north of the exploitation zone, at the edge of mining work. The distance between the location of the maximum subsidence and that of the maximum residual subsidence is 700 m. If one adopts the maximum value of residual subsidence of 55 cm, residual subsidence is equal to 5% of maximum subsidence. The residual tilt can be calculated using the empirical relation (§ 2). In this case this residual tilt is equal to 0.2 %, the maximum tilt increased from 1.8% (before residual subsidence phase) to 2% (after residual subsidence phase).

7.5. Subsidence effects on structures of Morsbach city

We determined the number of structures damaged induced by the exploitation. All concerned structures are located at the west of the exploited zone, under Morsbach city. Before 1991, the exploitation carried on non-urbanised area. The data thus relating to the three following periods are summarized in table 3.

Damage type	Recent panels 1991-1995	Residual phase 1996-1998	Stabilized phase 1999-2003
Architectural	41	44	13
Functional	29	5	10
Structural	4	2	1
Total	74	50	24

Table 3: Number of damaged structures due to exploitation at Morsbach city

Let us specify that certain structures were considered in several classes of damage of which we held account in our analysis. The total number of cases was 74 for the period 1991-1995; it is of 24 cases for the period of 1999-2003. The total number of damaged structures thus clearly decreased between 1996 and 2003. It is noted that the number of cases of structural damage is significantly decrease. The total number of cases corresponding to the structural damage is 7 compared to 148 retained. Only one case of structural damage was retained for stabilized phase. According to the observations, this case has been appeared during the active phase of subsidence and only declared during residual phase.

8. Conclusion

In this study, we present an analysis of the residual subsidence measured after the closure of the exploitation. The studied sector was Marienau – Morsbach city. The exploitation ended at the end of 1996. The maximum subsidence measured at the centre of the trough corresponds to the forecast given by empirical calculation. The basin has a dissymmetrical form. The maximum tilt in the East (non-urbanized zone) is 10% but reaches only 2% in the west (urban zone of Morsbach city). Residual subsidence is obtained after less than 2 years. This duration is in conformity with the forecast. The amplitude of residual subsidence is less than 5 % of total maximum subsidence at the centre of the trough. The supplement of maximum tilt due to residual subsidence is estimated at 0.2%. The damage of the structures is especially associated to the active phase of subsidence. After the period of stabilization, the number of complaints falls appreciably. The complaints are primarily due to late declarations of the existing damage.

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