Arch. Min. Sci., Vol. 58 (2013), No 1, p. 119–130

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.2478/amsc-2013-0008

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LONG- AND SHORT-TERM PROCESSES INDICATED BY THE DISPLACEMENT OF THE CHAMBER ROOFS IN THE MONUMENTAL WIELICZKA SALT MINE

DŁUGO- I KRÓTKOTRWAŁE PROCESY SYGNALIZOWANE PRZEMIESZCZENIAMI STROPU KOMÓR W ZABYTKOWEJ KOPALNI SOLI WIELICZKA

This paper presents several processes that are characteristic for the salt rock mass, which have been found upon analysis of observations of the chamber roof displacements in the monumental Wieliczka Salt Mine. Those processes are revealed in different time frames and they range from short- to long-term ones. A regular long-term increase or decrease of creeping rate in the chamber roof is expressed by power function of time. It was found that an annual component of that process consists in the season cycle, marked by increased displacement rates in the summer and reduced ones in the winter. The seasonal changes in air humidity are the cause of those cycles. A rock slip cycle is observed in some chambers during several months. In those periods, we can identify displacements that happen when internal static and dynamic friction is overcome. In 2007-2009, single signals from large-area rock-mass movements were recorded in several chambers. They were probably associated with the change of geo-mechanical conditions in northern region of rock mass after a leak had been plugged in the cross-corridor Mina. The results of our analysis have revealed new cognitive components contributing to the description of rock behaviour in specific geological and mining conditions of Miocene salt deposits.

Keywords: salt mines, displacement of chamber roofs, rock-mass creep, “stick-slip” process

W zabytkowej kopalni soli Wieliczka od 1995 r. prowadzone są pomiary przemieszczeń stropu w wybranych komorach, głównie w obrębie trasy turystycznej. W tej pracy przedstawia się wyniki tych pomiarów w 9 komorach. Sposób założenia czujników przemieszczeń przestawiono na rysunku 1. W pomiarach rejestruje się przyrost odległości między punktem umocowania bazy pomiarowej w odległości 10 m, a powierzchnią stropu wyrobisk. Częstotliwość pomiarów jest zróżnicowana, od kilku dni do kilku miesięcy.

Długotrwałe przemieszczenia stropu w okresie wieloletnim wykazują stałą tendencję ruchu, którą opisuje funkcja potęgowa (1). Uzyskane wartości parametru m w granicach od 0,90 do 1,25 określają długotrwałą tendencję ruchu. Dla $m = 1$ prędkość przemieszczeń jest stała, dla $m > 1$ podwaja się w okresie τ, a przy $m < 1$ dwukrotnie maleje. Na rysunkach 2 i 3 pokazano wyniki pomiarów przemieszczeń stropu w komorach Warszawa, Pieskowa Skała, Staszic i Maria Teresa, a w tabeli 1 uzyskane z aproksymacji wzorami (1) i (2) prognozowane wartości prędkości v i przyrostu obniżeń stropu Δw po 100 latach oraz

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czas dwukrotnej zmiany prędkości τ. W komorze Warszawa w okresie 16 lat prędkość przemieszczeń wzrasta dwukrotnie.

W okresie rocznym ujawnia się sezonowa tendencja ruchu z charakterystycznym wzrostem prędkości przemieszczeń w stropach komór w okresie letnim i spadkiem tej prędkości w okresie zimowym. Stosunek tych prędkości określa się wskaźnikiem procesów sezonowych f (3). W komorach Kaplicy Św. Kingi i Warszawa (rys. 5) f osiąga wartość odpowiednio 3,9 i 5,5, a w komorze Pompowni (rys. 4) wartość 6,1. Okresowe – sezonowe zmiany prędkości przemieszczeń spowodowane są wpływem wilgotności powietrza kopalnianego. Uwzględniając zmiany sezonowe, funkcja (1) przechodzi w funkcję (3), a jej zastosowanie przedstawiono w komorze Pompowni na rysunku 6.

Przesunięcia w kruchym ośrodku sprężysto-lepkim wyjaśnić można znanym procesem przekraczania granic tarcia statycznego i dynamicznego, określane terminem *stick-slip* (Jaeger i in., 2007) (rys. 7). Ruch taki obserwowany jest w obrębie górnych poziomów kopalni w komorach Staszic i Pieskowa Skała (rys. 8). Wykres omawianych przemieszczeń tworzy krzywą „schodkową”. Wartość skokowego przyrostu przemieszczeń może być w przybliżeniu stała. Jeżeli prędkość przemieszczeń w fazie tarcia dynamicznego rośnie, to wskazuje, że współczynnik tarcia dynamicznego maleje (rys. 8 lewy). Długookresowym efektem cyklicznego procesu, jest regularna postać krzywej pełzania w postaci funkcji potęgowej (1). Proces *stick-slip* w tych warunkach jest krótkookresowym cyklicznym elementem pełzania górotworu. Zjawisko to występuje wtedy, gdy współczynnik tarcia statycznego jest większy niż tarcia dynamicznego, a okres pomiarów jest znacznie mniejszy niż okres występowania skokowych przyrostów przemieszczeń.

Wyniki obserwacji pokazują także prawie jednoczesne występowanie sygnałów jednorazowych lub seryjnych, w wielu miejscach komór lub nawet w kilku komorach (rys. 9 i 10). W komorach Spalona, Haluszka i Warszawa sygnały te ujawniają się w latach 2007-2009, co wskazuje na to, że przyczyną tego mogła być wielkoobszarowa zmiana warunków geomechanicznych prawdopodobnie po zamknięciu wycieku w poprzeczni Mina w 2007 r., która spowodowała trwające do dziś wypiętrzenia terenu na północnym przedpolu kopalni w trakcie przywracania naturalnych warunków hydrogeologicznych.

Ujęcie ilościowe, opisanych w tej pracy procesów, jest warunkiem rozpoznania mechanizmu procesów pełzania w specyficznych warunkach kopalni Wieliczka. Służyć także może w przyszłości sformułowaniu kryteriów bezpieczeństwa, oceny i prognozy zachowania się stropów komór.

Słowa kluczowe: kopalnie soli, przemieszczenia stropu komór, pełzanie górotworu, „stick-slip” proces

1. Introduction

The physical phenomena occurring in the rock mass are described in various size and time scales. The time scale, applicable to rock deposit space or particular workings, is limited by second-long dynamic processes and century-long geological diastrophic processes. During the period of the Salt Mine's existence, long-term mechanical processes developed slowly, generally in a continuous manner, with chamber convergence associated with the reinstatement of hydrostatic stress around workings (Kortas, 2006, 2008). In specific conditions, the convergence process may result from quakes in rock mass, with a sudden change of stress conditions and discontinuous deformations (Canciara, 2010), even with the occurrence of subsidence and water penetration (Minkley & Menzel, 1993). Owing to the water hazard and the necessity to stop the rock-mass movement, as it was the case in the Wieliczka Salt Mine (d'Obyrn, 2011, 2012; Gonet et al., 2012), the rock behaviour observations should provide data for current fall of roof hazard evaluation and long-term process forecasting. This paper presents the rock-mass movement symptoms signalled by displacements whose causes and effects are associated with the time scale.

The monumental Wieliczka Salt Mine owes its long-term existence to favourable geo-mechanical conditions within the mine's upper levels. Those conditions are monitored by rock-mass movement measurements. Observations of the chamber roof displacements along the underground tourist route are constitute part of the system. Precise displacement recordings were started in 1995 upon installation of 54 Orzepowski's CRN detectors in 20 chambers, the same as applied in the KGHM Copper Mine (Orzepowski & Butra, 2004). A preliminary description of the observation results was presented by Kortas (2004). Here, we have used the measurement results obtained by J. Kwapin and A. Biel in 1995-2011.

The analysis conducted in the present study entails the displacement observation results involving the roofs of nine chambers, selected based on their similar geological and mining conditions, considerable chamber sizes, and long-term measurements. The analysis aims at the identification of characteristic symptoms that are revealed in various time scales. The scales include long-term and seasonal changes in the roof movement, as well as short-term process signals. In our interpretation of the measurement results, we point out the movement trends and their periodic repeatability, as well as similarity of symptoms both within particular chambers and within a wider rock-mass area. We have described those results with simple time functions, with coefficient and parameter values specified in figures. Our cognitive and practical conclusions are mentioned in our study conclusions.

2. Long-term Chamber Roof Displacement Trends

The assumptions of the observation project conducted by the Salt Mine included long-term recording of the chamber roof displacements along the tourist route. The designs of the measurement devices allow to determine displacements between point K in the chamber roof rock mass and point P in which the measurement base is anchored, within the distance from 10.0 to 10.8 m from the roof (Fig. 1). The detectors record the base distance increases $w_k(t)$, within the roof layer. The chamber roof is made of salt series rocks, sometimes lithologically diverse, and not always arranged in parallel packages. Measurements do not include recognition of the displacement or deformation distribution in the intermediate base section, or determination of total roof subsidence $w_p + w_k$ (Fig. 1). Determination of the measurement accuracy, resulting from measurement uncertainty and errors associated with the stabilization of devices in the rock mass, was not the object of this study. The measurement frequency in various chambers ranged from several days to several months.

Long-term chamber roof movement trends can be determined on the basis of the observations conducted in several monumental chambers located at upper levels: Pieskowa Skała, Staszic,

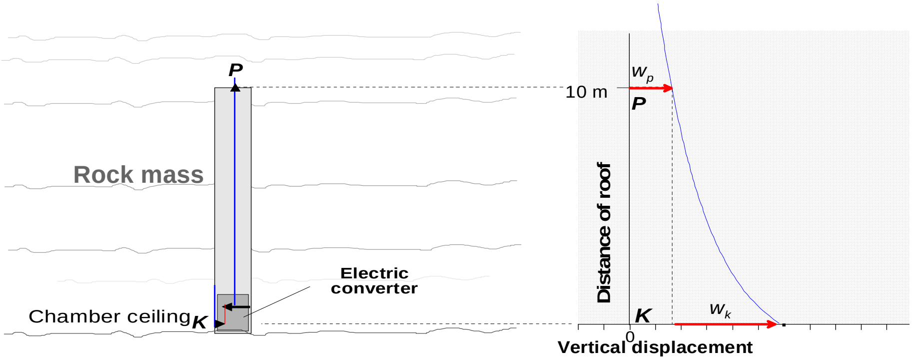

Fig. 1. Displacement of measurement base ends P-K

Maria Teresa, and Warszawa. The observed displacements, as shown in Figs. 2-5, are well approximated by power function $w(t)$, in the form of:

$$\begin{aligned} w(t) &= \Delta w_j [(t-t_0)/t_j]^m , \\ dw/dt &= v(t) = m v_j [(t-t_0)/t_j]^{m-1} \end{aligned} \tag{1}$$

Where Δw_j is the displacement in the first year of observation, t_0 is the initial time (e.g. 1995.34th year), t_j is a time unit (e.g. $t_j = 1$ year), $v_j = \Delta w_j / t_j$ is the displacement velocity in the first year of observation, and m is the power coefficient. If $m < 1$, the displacement rate is decreasing, at $m = 1$, the rate is constant, and at $m > 1$, the rate is increasing. Let τ determine the time after which the displacement rate is increasing or decreasing twice. Then:

$$\tau = t_j \, 2^{\frac{k}{m-1}} , \quad \text{where} \quad k = 1 \quad \text{for} \quad m > 1, \quad \text{or} \quad k = -1 \quad \text{for} \quad m < 1 \tag{2}$$

For example, at $m = 1.20$, the time of double *increase of velocity* τ is 32 years, and at $m = 0.75$, the time of double *decrease of velocity* is $\tau = 16$ years.

Currently, the displacement rate observed in the Warszawa chamber is small, although it increases in time (Fig. 2). Our analysis indicates that power coefficient m for detectors dR-35, dR-36, and dR-37 is the same and equals 1.25. The period of doubling the displacement rates τ in that chamber is short, and it amounts to 16 years.

The roof displacement rate increase trend also occurs in the Pieskowa Skała chamber (Fig. 2), where the power coefficient for detectors dR-176 and dR-159 is $m = 1.22$.

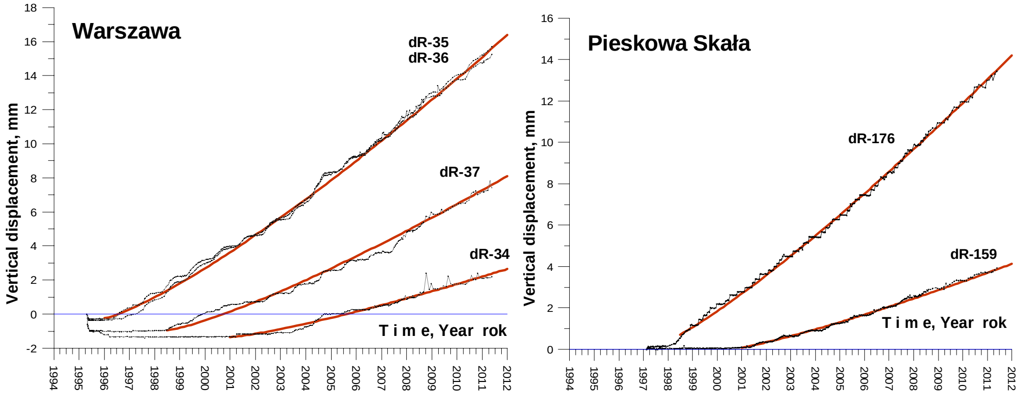

Fig. 2. Long-term displacement trends in the Warszawa and Pieskowa Skała chambers

The values of m in the Staszic chamber, obtained from approximation (Fig. 3), are close to 1, which means that the displacement rate is practically constant. The largest increase of the displacement rate was found at detector dR-180, where $m = 1.08$.

A slight decrease of displacement rates was observed in the Maria Teresa chamber (Fig. 3): $m = 0.90$ for detector dR-40 and $m = 0.96$ for detector dR-195.

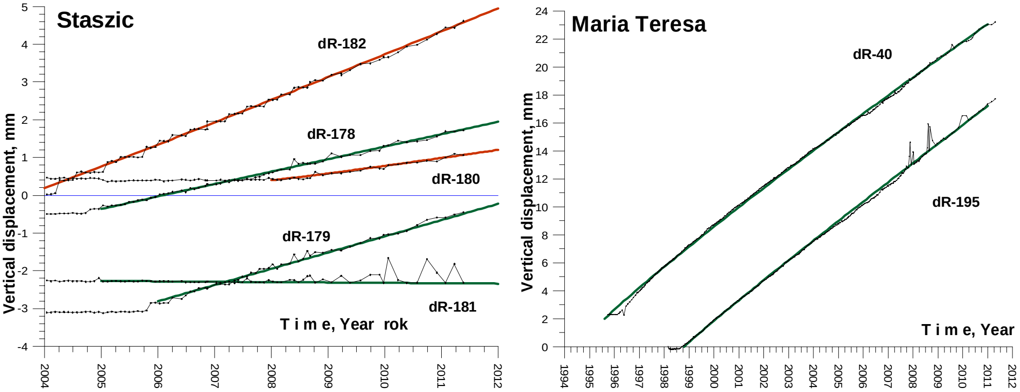

Fig. 3. Long-term displacement trends in the Staszic and Maria Teresa chambers

Parameter *m* (1) is the indicator of the current movement trend, and its determination allows us to compare the roof rock creep process in various chambers and forecast the displacement development in the next years to come. Table 1 presents the values of power coefficient *m*, velocity of displacements in the 1st and the 100th year of observation, roof subsidence after 100 years of observation $w_{100\ \text{years}}$, and the time of double change of displacement velocity τ. In the Pieskowa Skała and Warszawa chambers, the displacement increase will exceed 10 cm during 100 lat, and the displacement rate will increase four times in the Warszawa chamber roof.

TABLE 1

Values of the function (1) indicators for several chambers

Chamber	**Detector**	m	v_j **mm/year**	$v_{100\ \text{years}}$ **mm/year**	τ **years**	$w_{100\text{years}}$ **mm**
Pieskowa Skała	dR- 32	**1.22**	0.21	0.70	23	58
Pieskowa Skała	dR-176	**1.22**	0.54	1.86	23	149
Staszic	dR-180	**1.08**	0.18	0.28	> 1000	26
Staszic	dR-179	**1.00**	0.33	0.33	∞	33
Staszic	dR-182	**1.04**	0.54	0.67	> 1000	65
Maria Teresa	dR-195	**0.96**	1.56	1.24	> 1000	130
Maria Teresa	dR- 40	**0.90**	1.84	1.04	1024	116
Warszawa	dR- 34	**1.25**	0.20	0.79	16	62
Warszawa	dR- 37	**1.25**	0.35	1.38	16	111
Warszawa	dR- 36	**1.25**	0.52	2.05	16	164

The approximations of long-term displacement observations, using the power function with constant parameters, indicate that the mining conditions are stable in that time scale. If the conditions remain stable, the currently observed movement trend will continue in the years to come. Power function parameter *m* is therefore an indicator of a long-term creep trend of the observed chamber roofs. The decrease of the roof displacement rates is beneficial for the rock-mass stability maintenance. Excessive increase of the rate would require search for causes of the process.

3. Seasonal Movement Trends: Influence of Humidity on Chamber Roof Displacements

Next to non homogenous of rocks, humidity is the basic factor activating the rock mass movements in salt mines. Laboratory tests on salt sample creep indicated that a dozen percent humidity increase causes that creep rate increases by several times. Water, which is present in the deposit, originates from mine leaks and penetration of brine from excavation filling works. Humidity is also present in the mine air. Mine air humidity depends on the water content in the atmospheric air and the length of the air flow path through workings during which flow air is drying through the contact with salt rocks. In the summer time, air temperature and humidity introduced into the mine are the highest, although the temperature is not changing annually in workings. Also, steam exhaled by tourists is a source of water in the mine air.

The influence of humidity is clearly recorded in displacement observations. It is especially visible on some chamber roofs owing to the presence of clay. The results of the measurements taken in the Pumping Station chamber, which is not visited by tourists (Fig. 4) are good examples of displacement rate fluctuations during the year. The influence of humidity can also be seen in the Warszawa chamber and even in the St. Kinga’s Chapel (Fig. 5). A similar process was also observed in the Ważyn chamber of the Bochnia Salt Mine (Kortas, 2004).

The influence of seasonal displacement rate fluctuations f can be determined by the proportion of periodic displacement rates, or:

$$f = (\Delta w_1/\Delta t_1)/(\Delta w_2/\Delta t_2), \tag{3}$$

Where $\Delta w_1/\Delta t_1$ determines the average displacement rate in the summer, while $\Delta w_2/\Delta t_2$ does the same in the winter._

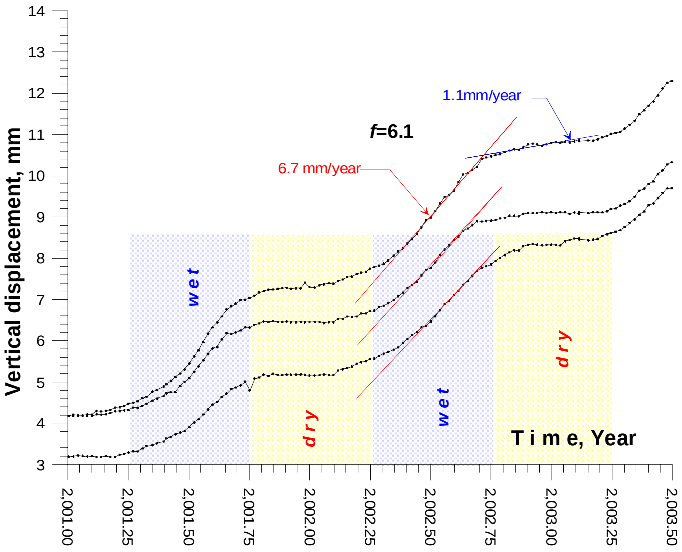

Fig. 4. Seasonal changes of the roof displacement increases in the Pumping Station chamber

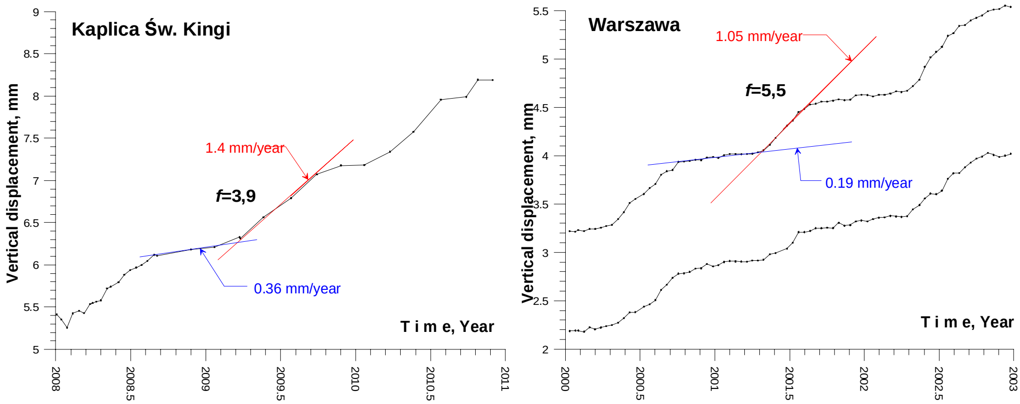

Fig. 5. Seasonal changes of the roof displacement increases in the St. Kinga's Chapel and the Warszawa chamber

The influence of seasonal displacement rate fluctuations f in the Pumping Station chamber reaches 6.1, with $f = 5.5$ in the Warszawa chamber, and $f = 3.9$ in the St. Kinga's Chapel. Reduction of mine air humidity would cause a considerable decrease of the chamber convergence rate.

The expansion of equation (1) into a two-part periodic function in the following form is an example of approximation that connects the seasonal displacement fluctuations with the general roof displacement long-term trend (4):

$$w(t) = \Delta w_j \left(\frac{t-t_0}{t_j}\right)^m + A\sin\left[2\pi\left(\frac{t+0,5}{t_j}\right)\right] \qquad (4)$$

Where A is the amplitude of seasonal fluctuations (Fig. 6).

For the Pumping Station chamber and detectors dR-196 and dR-202, parameter A amounted to 0.40 and 0.47 mm, respectively (Fig. 6). If $A = 0$, process seasonality is neglected and function (4) transforms into function (1).

4. Static and Dynamic Short-Term Processes

Displacements in the brittle elastic-viscous medium can be explained with the process of exceeding static and dynamic friction boundaries. That phenomenon called *stick-slip* is known in mechanics and many technological processes, as well as rock mechanics (Jaeger et al., 2007). This process is opposite to rock folding, with continuity preservation (Brace & Byerlee, 1966). A model of that process is shown in Fig. 7.

Short-term process measurements are not complete, although we can clearly see a fast increase of displacements, followed either by the rate decrease and displacement stop (Fig. 8, upper right side) or a regular rate increase in particular cycles (Fig. 8, left-hand side). We can also notice a time coordination of the stepped movement. The observed stepped increase of displacements can result from the influences of movement sources located nearby or far away from the monitor-

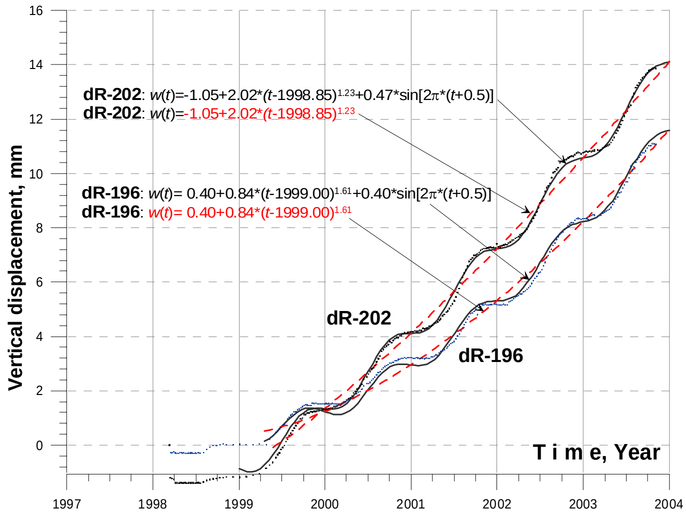

Fig. 6. Displacement approximation in the Pumping Station chamber: continuous line, equation (4): dotted line, equation (1)

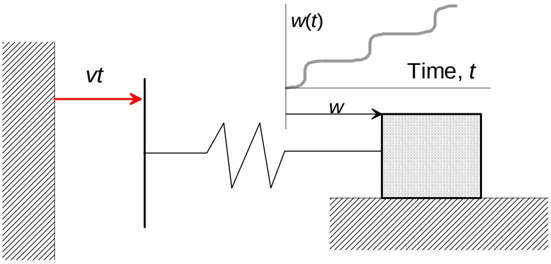

Fig. 7. Mechanical model of the *stick-slip* process (Jaeger et al., 2007)

ing devices. The time coordination of the stepped displacement increase may indicate a common source in the case of the Pieskowa Skała and Staszic chambers (Fig. 8, lower right side).

We can distinguish two characteristic effects in that phenomenon: a sudden stepped displacement increase after static friction has been overcome, followed by a slow displacement overcoming dynamic friction when the collected energy is transformed into heat and dissipated. If the increase of energy needed for movement perpetuation is not adequate, the movement stops and the energy is accumulated until static friction is overcome again. That phenomenon occurs when the static friction coefficient is larger than that of dynamic friction. The cycle with period t_s is repeated. The concurrence of the stepped movement identified at two detectors (Fig. 8, lower right side) indicates that the measurement device's effect is not a cause of that phenomenon, because in such a case the stepped increase initiation would rather be random.

The graph of the displacements under discussions creates a stepped curve. The value of the stepped displacement increase can be constant, and the displacement rate is increasing at

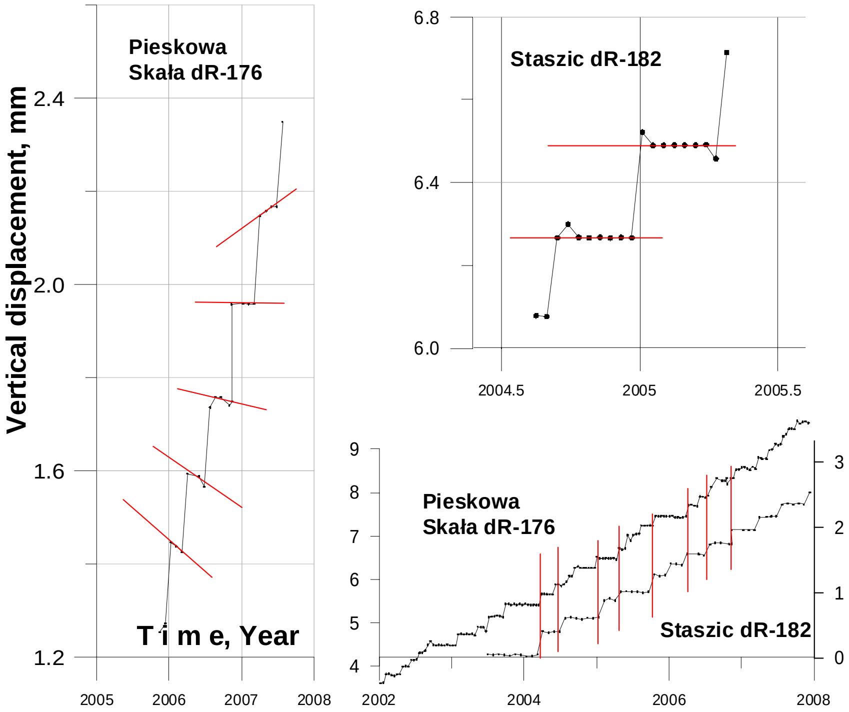

Fig. 8. Short-term displacements recorded in the Pieskowa Skała and Staszic chambers

the dynamic friction stage (Fig. 8, left-hand side). This observation indicates that the dynamic friction coefficient is decreasing at the constant static friction coefficient.

The possibility of recording of that phenomenon depends on observation frequency. If the time between observations t_o was longer than $t_s/2$, the stepped form of the displacement curve would not be recorded. For that reason, when measurement frequency t_o is stable, such a roof movement is noticed in the chambers located at small depths. A similar phenomenon occurs at larger depths, but observations would require increased measurement frequencies.

A regular form of the creep curve, in the form of an power function, is a long-term effect of that cyclic process. The *stick-slip* process is a short-term cyclic element of rock-mass creep in the mine conditions.

5. Large-Area Process Signals

A review of the displacement observation results indicates almost concurrent occurrence of single or serial signals in many places of a chamber, or even in several chambers. The co-occurrence of signals in the Layer and Spalona and Warszawa and Haluszka chambers is an example of that phenomenon.

In the Layer chamber at Level VII, seasonal displacement rate fluctuations were marked initially in 2001 (Fig. 9), but later the displacement rate stabilized, with a decrease trend ($m = 0.91$).

In 2008, sudden displacement increase and decrease were observed in three locations (detectors), followed by the damage of detector dR-198. Similar displacement fluctuations also occurred in other chambers during the same period (Fig. 10). If the movement trend changes after a sudden displacement increase, its source or cause occurs on the roof subjected to observation or nearby, just like in the case of the Spalona chamber (Fig. 10, upper side). The records from the Layer (Fig. 9), Spalona (Fig. 10, lower side), Haluszka, and Warszawa (Fig. 10) chambers are the examples of the effects caused by distant sources.

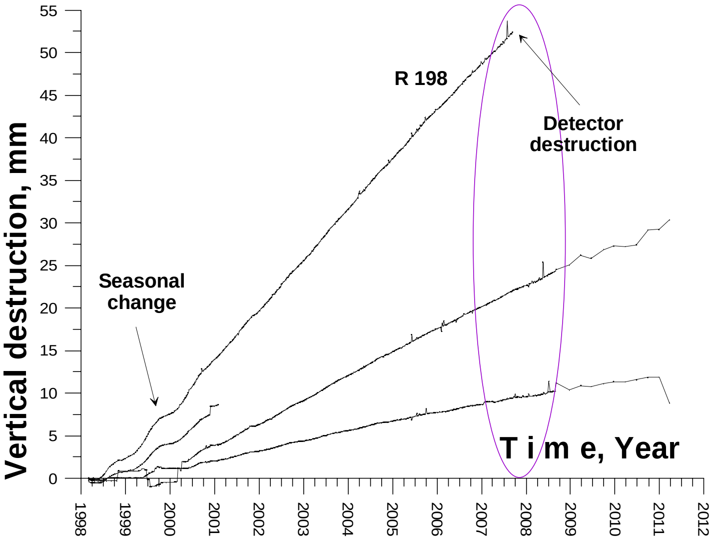

Fig. 9. Roof displacements in the Layer chamber (former Fornalska chamber)

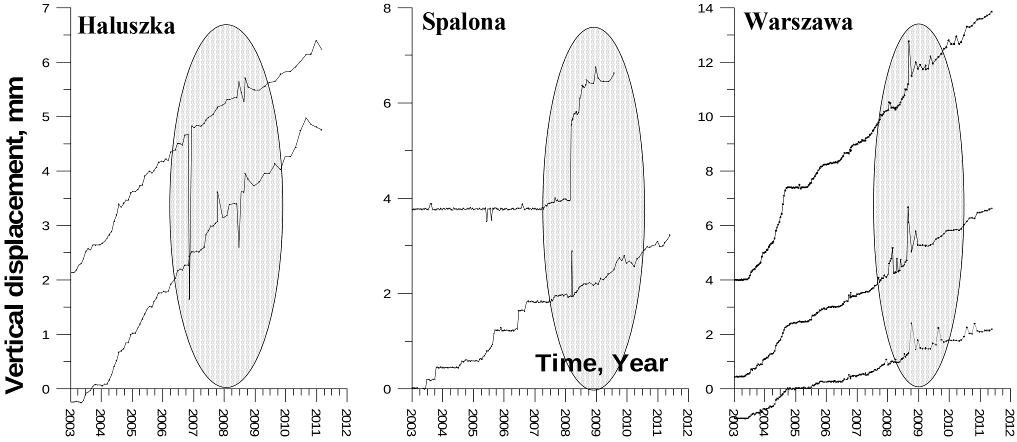

Fig. 10. Short-term displacement increases in the Haluszka, Spalona, and Warszawa chambers

Extreme movement rates calculated from the measurements are shown in Fig. 11. Owing to the measurement frequency, we are rather dealing with the signals of the current processes than actual records.

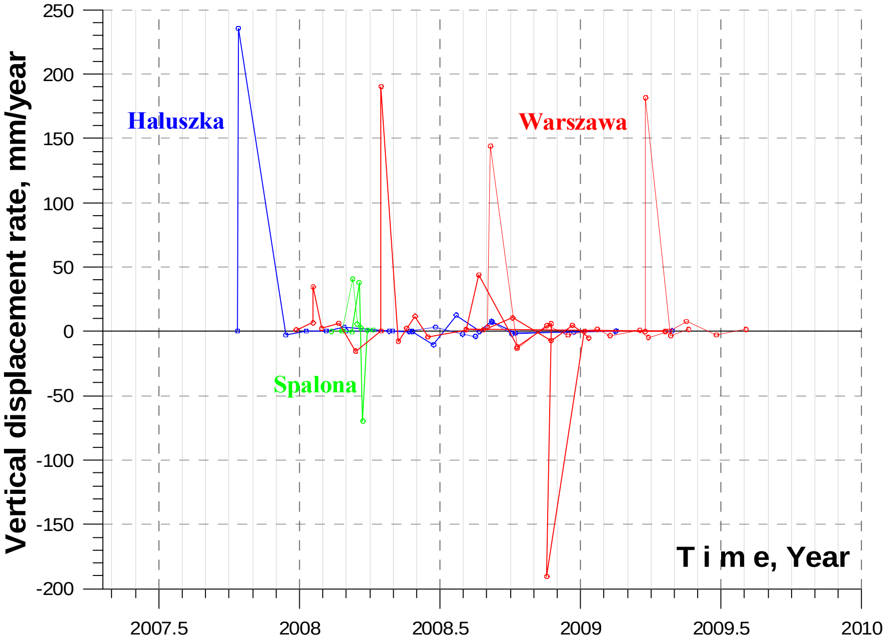

Fig. 11. Vertical displacement rates in several chambers in 2007-2009

The effects under discussion could have been caused by the rock-mass movements on a large scale, associated with the influences of the mine workings that also cause the formation of subsidence on the land surface. Owing to the concentration of signals in 2007-2009, we can conclude that the detectors recorded rock-mass load fluctuations resulting from the liquidation of a water depression cone after leaks were plugged in the Mina cross-corridor. Consequently, geo-mechanical conditions changed at the northern deposit boundary. Since 2007, new geo-mechanical conditions have been developing at the foreground of the Mina cross-corridor, and they are indicated by the continuous rock-mass uplift observed above that area.

6. Conclusions

This study presents the results of long-term measurements of the chamber roof subsidence in the Wieliczka Salt Mine. On a long-term time scale, roof displacements indicate a regular rate increase or decrease trend. Those phenomena can be described with an power function whose power coefficient *m* indicates a long-term creep trend. By applying that approximation, we can forecast further displacements and compare the behaviour of various chamber roofs.

Seasonal winter/summer fluctuations influence the periodic displacement rate increases and decreases, and the proportion of rate *f* reached the values from 3.9 to 6.1 in three chambers. The displacement rate increase in the summer is assigned to the increased humidity of mine air and the salt deposit silt rock wetting processes.

In short time ranges, we observe a stepped displacement increase process, with a stage of a sudden displacement increase and a stage of either slow displacement or movement stopping. That phenomenon was explained by the fact that static and dynamic friction was overcome by loads. The time coordination of that phenomenon within one or among several chambers was shown on the example of displacements found in the Staszic and Pieskowa Skała chambers.

Sudden momentary displacement increases and decreases were observed in many chambers. Their concentration occurred in 2007-2009. A hypothesis states that the phenomenon could have been caused by a large-area change in the geo-mechanical conditions after leaks had been plugged in the Mina cross-corridor in 2007. Plugging caused continuous land uplift on the northern mine's foreground during the restoration of natural hydro-geological conditions.

Quantitative measurements of the processes described in this work are a precondition of the recognition of the creep process mechanism in the unique conditions of the Wieliczka Salt Mine. This can also serve formulation of the safety criteria and evaluation and forecasting of chamber roof behaviour in the future.

The author would like to thank the Management Board of the Wieliczka Salt Mine for access to the data and documentation used in this study.

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Received: 26 June 2012