Studying the Kaiser Effect During Modeling of Rock Loading Conditions Using the NX-borehole Jack

N L Beltyukov

Mining Institute of the Ural Branch of the Russian Academy of Sciences, 78a Sibirskaya St, Perm, Perm Krai 614007, Russian Federation

E-mail: bnl@mi-perm.ru

Abstract. The paper deals with modeling the stress state experienced by rocks in a loaded around-borehole volume to justify a promising method of in-situ stress measurements based on the Kaiser effect. Mathematical modeling of loading the horizontal borehole walls with a NX-borehole jack in a direction of principal components $\sigma_1$ or $\sigma_3$ of the natural stress field was performed for conditions of the unperturbed salt rock mass of the Verkhnekamskoe potassium salt deposit. As a result of the numerical calculation of stresses, it was determined that recovery of radial component $\sigma_r$ in compression regions of the rock volume around the borehole occurs when the jack’s pressure reaches the initial value of the principal stress. At the same time, the concentration of tangential component $\sigma_\theta$ in these regions is retained. The rock salt specimens were tested under modes similar to the stress states of the rocks in the around-borehole volume to study the Kaiser effect under these conditions using a triaxial compression vessel. It was found that in the second loading cycle, the recovery of the initial values of axial component $\sigma_{axial}$ of the specimen stress field, unloaded after the first cycle, stimulates acoustic emission. This regularity is true for the case when there is no increase in confining pressure $\sigma_{conf}$ on the specimen between the cycles. In the conditions with an increase in confining pressure $\sigma_{conf}$ between the first and second cycles, the Kaiser effect is found at higher values of $\sigma_{axial}$ component than the initial ones. It is shown that the nature of the effect depends on a type of a specimen’s initial stress state and is caused by the growth resumption of longitudinal microcracks, if $\sigma_{axial} > \sigma_{conf}$ in the first loading cycle, or by a closure of lateral microcracks when $\sigma_{axial} < \sigma_{conf}$ in the first loading cycle.

1. Introduction

There are two basic instrumental methods of measuring in-situ stresses, i.e. hydraulic fracturing and borehole overcoring. These methods are being improved and make it possible to achieve a high degree of reliability of results. However, limited application conditions, as well as labor intensity and high implementation costs lead to emerging alternative methods, e.g. methods based on the Kaiser effect in rocks are of special interest [1-3]. Their advantage lies in the fact that to estimate the in-situ stresses, there is no need for difficult high-precision measurements of deformations and the use of the elasticity theory is not required. In this regard, such methods make it possible to determine stresses in the conditions of ductile and jointed rock masses, where other methods of measurements are constrained [4].

The Kaiser effect consists in the absence of acoustic impulses in geomaterials under cyclic loading until the maximum load level of the previous cycle is reached (figure 1). If a load exceeds this value, this leads to the resumption of acoustic emission (AE), which can be expressed in an abrupt increase in the AE hit rate (the number of hits per unit time). The effect was first discovered by J. Kaiser in 1953 during cyclic testing of metals [5].

The basis of measurement in-situ stresses using the Kaiser effect lies in the assumption that the rocks in the mass experience the first loading cycle due to gravitational and tectonic forces. By performing second loading cycle of rock specimens extracted from the mass under laboratory conditions, it is possible to estimate the normal component of the initial stress field acting in the loading direction [6-10]. However, this method has its disadvantages, the principal of which is the difficulty in interpreting...
the results due to differences between the stress state of rocks in the mass and during loading in laboratory conditions [11].

Figure 1. Illustration of a classic experiment to observe the Kaiser effect under cyclic loading of rock specimen. (a) The loading scheme of the specimen in the uniaxial compression conditions. (b) An idealized graph of changes in the axial load and AE hit rate under cyclic loading of the rock specimen.

The proposed approach in using the Kaiser effect to measure in-situ stresses is to unload a certain region of the rock mass by drilling a well and re-loading its walls with a Goodman NX-borehole jack with a simultaneous recording of AE signals (figure 2) [12-16]. The design of this jack enables a directional load to the rocks of the around-borehole volume, which makes it possible to estimate the components of the virgin stress field in different directions. The value of the component acting in the loading direction is taken as the pressure value in the hydraulic system, at which an abrupt increase in the AE parameters is observed: AE hit rate (figure 1b) or the total number of hits accumulated from the start of recording.

Figure 2. Illustration of the in-situ stress field components measurement in a horizontal well using the hydraulic jack: 1 – Goodman borehole jack; 2 – AE transducer; 3 – AE registration device; 4 – pressure gauge; 5 – hand pump; 6 – high-pressure hoses; 7 – coaxial cable.

When implementing the method of loading the around-borehole rock volume, it is assumed that only the stress field component acting in the direction of the loading axis is unloaded and recovered. If this assumption is correct, then this approach is more preferable, since the problem of mismatch between loading conditions in the second cycle and the initial stress state of rocks in the mass is resolved. In this regard, the work is focused on studying the features of changes in the stress state of the rocks of the around-borehole volume during loading with the hydraulic jack, as well as studying the Kaiser effect under such loading conditions.
2. Numerical modeling of the stress state of rocks in the around-borehole volume

Masses of ductile rocks, where other methods are constrained, are among major applications of the proposed method to measure stresses. Here the numerical 3D-modeling of stresses in the around-borehole rock volume was carried out for a horizontal well drilled in an unperturbed salt rock mass of the Verkhnekamskoye potash salt deposit (VPSD). To simulate ductile properties of the rocks, we used the non-linear model with Young’s modulus, depending on values of the acting stress: $E_1 = 2.5$ GPa (when $0 \leq \sigma < 0.5 \sigma_{ult}$), $E_2 = 1.0$ GPa (when $0.5 \sigma_{ult} \leq \sigma < \sigma_{ult}$), $E_3 = 0.0$ GPa (when $\sigma = \sigma_{ult} = 20.0$ MPa). Poisson ratio $\nu$ was taken equal to 0.3 [17]. The geometric model of the rock mass was a parallelepiped with a size of $0.8\times0.8\times0.2$ m, and the horizontal well was a through cylindrical hole in the center with a diameter of 76 mm. The natural stress state of the rocks in the mass was set by applying normal stresses to 5 faces of the parallelepiped, while the movement of the 6th lower face was limited. Vertical stress $\sigma_1$ was 8.0 MPa, which roughly corresponds to an average rock density of 2200 kg/m³ and a depth of 370 m. The vertical-horizontal stress ratio in the salt mass at a given depth according to the results of field studies [18] was 0.6. In this regard, stresses $\sigma_2 = \sigma_3 = 4.8$ MPa were set in the horizontal directions. The bearing plates of the hydraulic jack are simulated in the form of two thin sheets 1.5 mm thick and 200 mm long from a soft elastic material with the characteristics $E = 1.1$ GPa, $\nu = 0.42$. This choice of the thickness and properties of the material of the plates was caused by the need for them to copy the well contour shape when applying loads. Based on the experimental study results in [19], the constant of friction $\mu$ between the plates and the borehole wall was taken equal to 0.1. Stress calculations around the borehole were carried out for three cases: 1) without loading the borehole walls; 2) when loaded with the hydraulic jack in the direction of the maximum principal stress $\sigma_1$; 3) when loaded with the hydraulic jack in the direction of the minimum principal stress $\sigma_0$.

Results of the first stage of modeling the stress distribution in a plane orthogonal to the borehole axis, without loading its walls with the hydraulic jack, are shown in figure 3 in a cylindrical coordinate system, where $\sigma_r$ is the radial stress; $\sigma_\theta$ is tangential stress; $\sigma_z$ is axial stress. In this case, the classical way of stress distribution around a hollow cylindrical hole in a homogeneous continuous medium is obtained, which coincides with analytical solutions in [20]. A concentration of tangential component $\sigma_\theta$ of the stress field is observed in all directions around the well contour, while radial component $\sigma_r$ is unloaded. Axial component $\sigma_z$ is partially unloaded along the $y$ axis (figure 3a), and an increase in its values is noted in the direction of the $x$ axis (figure 3b). When the components are further from the borehole contour, all of them have their values recovered and correspond to the undisturbed stress field.

![Figure 3](image_url)

**Figure 3.** Distribution of stresses in rocks around the borehole without loading its walls: (a) in the direction of the $y$-axis; (b) in the direction of the $x$-axis.

When loading the borehole walls in the directions of principal stresses $\sigma_1$ or $\sigma_0$, we can say that the recovery of the initial values of radial component $\sigma_r$ occurs when the hydraulic jack pressure corresponds to the values $\sigma_1$ or $\sigma_0$ (figure 4). At the same time, the concentration of the tangential component $\sigma_\theta$ on the borehole contour in the compression regions is kept in both cases. Axial component $\sigma_z$ is recovered when borehole walls loading with the hydraulic jack in the direction of stress $\sigma_1$ (figure 4a), and it retains increased values when loading in the direction of stress $\sigma_0$ (figure 4b).
Figure 4. Distribution of stresses in rocks around the borehole when loading its walls with the hydraulic jack: (a) in the direction of the y-axis ($P = 8.0$ MPa); (b) in the direction of the x-axis ($P = 4.8$ MPa).

Thus, the rocks located near the contour of the borehole in the compression regions, successively experience three stages of the stress state, i.e. the initial state; the state after the borehole drilling; the second loading with the hydraulic jack. So the numerical modeling results can be generalized in the form of idealized time diagrams, displaying changes in the stress state of the rocks at these stages (figure 5). A common feature of the presented loading modes is the unloading and subsequent recovery of only component $\sigma_r$ of the stress field, while in the first case the unloaded component is the maximal initially (figure 5a), and in the second case it is the minimal (figure 5b). Further, to study the Kaiser effect under the considered conditions, physical modeling experiments of these stress paths were carried out on the specimens of salt rocks.

Figure 5. Idealized time diagrams of changes in the stress state of rocks located near the borehole contour in the direction to: (a) maximum principal stress $\sigma_1$; (b) minimum principal stress $\sigma_3$.

3. Physical modeling of the stress state of rocks in the around-borehole volume

A change in the stress state of rocks similar to conditions in the around-borehole volume, characterized by unloading and subsequent recovery of the minimum or maximum component of the in-situ stress field, makes it possible to implement a triaxial compression vessel of rock mechanics test system «MTS-815». This system allows testing cylindrical rock specimens with a diameter of up to 100 mm and a height of up to 200 mm according to the Karman-type ($\sigma_1 > \sigma_2 = \sigma_3$) and Böker-type ($\sigma_2 = \sigma_3 > \sigma_1$) loading conditions, with a maximum compressive force of 1500 kN and confining pressure up to 80 MPa. During the tests, acoustic emission impulses were registered using a piezoelectric transducer (the frequency range of 100-500 kHz) installed on the outside of the vessel on its lower part, and recording equipment «Vallen AMSY-6», synchronized with the signals of the test system. In order to reduce noise from running equipment, the AE detection threshold was set at 48 dB. Physical modeling experiments
of the loading conditions of rocks in the around-borehole volume were carried out using rock salt specimens taken from the salt mine of the VPSD, 100 mm in diameter and 200 mm in height.

Here is the description of how specimens were tested according to the conditions that simulate the stress path of the around-borehole rock volume loaded with the hydraulic jack in the direction of the principal stress $\sigma_1$. In the first cycle, the specimen was loaded in the Karman mode: the axial load $\sigma_{axial}$ was 8.0 MPa, the confining pressure $\sigma_{conf}$ was 4.8 MPa (figure 6). After 20 min, the maximum stress field component $\sigma_{axial}$ was unloaded to a value of 1.0 MPa, following which the initial values were recovered. The loading and unloading rates during the specimens testing were in the range of 2-4 MPa/min. It was found that the beginning of an intensive increase in AE hit rate occurs at values of the axial load somewhat lower than in the first cycle. However, the maximum level of rate is observed when stress $\sigma_{axial}$ reaches the value of the first cycle. Such a change in the AE hit rate corresponds to the Kaiser effect under cyclic loading of ductile rocks with a short holding time between the cycles [1].

![Figure 6](image_url)

**Figure 6.** An example of the results of testing specimens in the triaxial compression vessel according to a mode that simulates the conditions of loading rocks in the around-borehole volume using the hydraulic jack in the direction of principal stress $\sigma_1$.

In case of testing the specimens according to conditions that simulate the stress path of the around-borehole rock volume loaded with the hydraulic jack in the direction of principal stress $\sigma_1$, in the first cycle the specimen was loaded in the Böker mode: the axial load $\sigma_{axial}$ was 4.8 MPa, the confining pressure $\sigma_{conf}$ was 6.4 MPa (figure 7). After 20 minutes, the axial component of the stress field was unloaded to a value of 1.0 MPa, followed by its recovery with loading rate in the range of 2-4 MPa/min. In this case, two variants were considered: without changing the confining pressure and with an increase in the confining pressure to 10.4 MPa between the loading cycles. Experiments revealed that in the first variant, when the axial load reaches the values of the first cycle, an increase in the AE hit rate was observed (figure 7a). In the variant with an increase in the confining pressure, this effect was found at higher values of $\sigma_{axial}$ component than the initial ones (figure 7b). It was also found that when stress $\sigma_{axial}$ reaches the value of the confining pressure, i.e. when the stress state of the specimen is close to the hydrostatic ($\sigma_1 = \sigma_2 = \sigma_3$), the value of the AE hit rate has its peak.
The characteristic feature of the considered loading conditions for the salt rock specimens in the triaxial compression vessel is that in the case when the axial component values of the stress field are lower than the confining pressure, the specimen is in a stress state according to the Böker-type triaxial extension ($\sigma_{\text{axial}} < \sigma_{\text{conf}}$). This leads to axial tensile deformations of the specimen and the formation of lateral microcracks [21, 22] (figure 7). Whereas under loading according to the Karman-type triaxial compression ($\sigma_{\text{axial}} > \sigma_{\text{conf}}$), when the values of the axial component are greater than the value of the confining pressure, the specimen expands in the lateral directions and longitudinal microcracks are formed (figure 6). It is believed that the principal reason for the Kaiser effect’s occurrence in rocks is an abrupt increase in the AE hit rate caused by the growth resumption of the longitudinal microcracks when the load reaches the value of the previous cycle. The results of independent laboratory experiments confirm this mechanism for the cases of uniaxial compression and triaxial compression according to Karman-type loading [1, 23-26]. It should be noted that during the testing according to the conditions that simulate the stress path of the around-borehole rock volume loaded with the hydraulic jack in $\sigma_2$ direction (figure 6), the specimen for some time turns out to be in a state when $\sigma_{\text{axial}} < \sigma_{\text{conf}}$. However, it is permissible to assume that the Kaiser effect in the second cycle is also principally caused by the resumption growth of longitudinal microcracks.

In case of testing the salt specimens according to the conditions that simulate the stress path of the around-borehole rock volume loaded with the hydraulic jack in $\sigma_2$ direction (figure 7), an increase in the AE hit rate is started when the recovered component $\sigma_{\text{axial}}$ reaches or exceeds the value of the first cycle, but not more than the value of the confining pressure $\sigma_{\text{conf}}$. This means that the specimen is in a Böker-type stress state both in the first and in the second loading cycles, and the recovery of the $\sigma_{\text{axial}}$ component in the latter case leads to the closure of the lateral microcracks in the specimen. Until now, only an assumption has been made about the Kaiser effect’s occurrence in rocks due to the crack closure [24, 27] without the experimental confirmation. According to [24] a abrupt increase in AE hit rate during closure of cracks is possibly caused by the destruction of roughness on their surfaces when they start to contact each other. Thus, the observed increase in the AE hit rate in the second cycle, if the restored component $\sigma_{\text{axial}}$ was less than the confining pressure $\sigma_{\text{conf}}$ in the initial stress state, can be attributed to the Kaiser effect in salt rocks.

Figure 7. An example of the results of testing specimens in the triaxial compression vessel according to a mode that simulates the conditions of loading rocks in the around-borehole volume using the hydraulic jack in the direction of the principal stress $\sigma_2$: (a) without changing the confining pressure; (b) with an increase in the confining pressure.

4. Discussion of results

The characteristic feature of the considered loading conditions for the salt rock specimens in the triaxial compression vessel is that in the case when the axial component values of the stress field are lower than the confining pressure, the specimen is in a stress state according to the Böker-type triaxial extension ($\sigma_{\text{axial}} < \sigma_{\text{conf}}$). This leads to axial tensile deformations of the specimen and the formation of lateral microcracks [21, 22] (figure 7). Whereas under loading according to the Karman-type triaxial compression ($\sigma_{\text{axial}} > \sigma_{\text{conf}}$), when the values of the axial component are greater than the value of the confining pressure, the specimen expands in the lateral directions and longitudinal microcracks are formed (figure 6). It is believed that the principal reason for the Kaiser effect’s occurrence in rocks is an abrupt increase in the AE hit rate caused by the growth resumption of the longitudinal microcracks when the load reaches the value of the previous cycle. The results of independent laboratory experiments confirm this mechanism for the cases of uniaxial compression and triaxial compression according to Karman-type loading [1, 23-26]. It should be noted that during the testing according to the conditions that simulate the stress path of the around-borehole rock volume loaded with the hydraulic jack in $\sigma_2$ direction (figure 6), the specimen for some time turns out to be in a state when $\sigma_{\text{axial}} < \sigma_{\text{conf}}$. However, it is permissible to assume that the Kaiser effect in the second cycle is also principally caused by the resumption growth of longitudinal microcracks.

In case of testing the salt specimens according to the conditions that simulate the stress path of the around-borehole rock volume loaded with the hydraulic jack in $\sigma_2$ direction (figure 7), an increase in the AE hit rate is started when the recovered component $\sigma_{\text{axial}}$ reaches or exceeds the value of the first cycle, but not more than the value of the confining pressure $\sigma_{\text{conf}}$. This means that the specimen is in a Böker-type stress state both in the first and in the second loading cycles, and the recovery of the $\sigma_{\text{axial}}$ component in the latter case leads to the closure of the lateral microcracks in the specimen. Until now, only an assumption has been made about the Kaiser effect’s occurrence in rocks due to the crack closure [24, 27] without the experimental confirmation. According to [24] a abrupt increase in AE hit rate during closure of cracks is possibly caused by the destruction of roughness on their surfaces when they start to contact each other. Thus, the observed increase in the AE hit rate in the second cycle, if the restored component $\sigma_{\text{axial}}$ was less than the confining pressure $\sigma_{\text{conf}}$ in the initial stress state, can be attributed to the Kaiser effect in salt rocks.

5. Conclusion

To justify the promising method of in-situ stress estimating based on the Kaiser effect in the loaded around-borehole rock volume, we modeled the stress state experienced by the rocks under these conditions. As a result of the mathematical modeling of stresses around the well in cases of loading its walls with the hydraulic jack in the directions of the principal stresses $\sigma_2$ or $\sigma_1$, it was found that when the hydraulic jack’s pressure reaches their virgin values, radial component $\sigma_3$ of the stress field, unloaded
after the well drilling, is recovered. At the same time, the stress field in the compression regions is not reduced to the initial state, since the concentration of tangential component $\sigma_\theta$ on the borehole contour is preserved for the considered conditions of the "jack-borehole" contact.

Physical modeling using the salt rock specimens of similar stress paths, which consists in unloading and subsequent recovery of axial component $\sigma_{\text{axial}}$ of the stress field, showed an increase in the AE hit rate in the second cycle when stress $\sigma_{\text{axial}}$ is close to the value of the first cycle, if the confining pressure $\sigma_{\text{conf}}$ on the specimen was not increased between the cycles. An increase in component $\sigma_{\text{conf}}$ causes the Kaiser effect at higher values of axial component $\sigma_{\text{axial}}$ than the initial ones. It should be noted that for a more detailed study of the influence of tangential stresses $\sigma_\theta$ concentration near the well contour on the hydraulic jack pressure, at which the Kaiser effect occurs, further studies are required that take into account the pronounced rheological properties of salt rocks, and the related features of stress distribution around the well.

The obtained results are of significant scientific interest, as the Kaiser effect was detected in a specific conditions of the salt rock specimens loading according to the Böker mode, similar to loading the borehole walls with the hydraulic jack in the direction of the principal stress $\sigma_\theta$. It is also shown that the effect in this case is most likely caused by the microcrack closure mechanism in the rock. Having received the experimental confirmation, this mechanism can be used to develop a mathematical model describing the presence of the Kaiser effect in the rocks of the around-borehole volume.

Acknowledgments

The reported study was funded by RFBR (project No. 20-45-596011) and Ministry of Science and Higher Education of the Russian Federation (theme No. 0422-2019-0007-C-01). The experimental results were obtained using equipment of Collective Use Center “Study center of geomaterial properties” of Perm National Research Polytechnic University.

References

[1] Lavrov A V, Shkuratnik V L, Filimonov Yu L 2004 Acoustic emission effect of memory in rocks (Moscow: Moscow State Mining University) p 456
[2] Zang A, Stephansson O 2010 Stress Field of the Earth’s Crust (Dordrecht: Springer) p 322
[3] Nikolenko P V, Shkuratnik V L, Chepur M D, Koshelev A E 2018 Using the Kaiser effect in composites for stressed rock mass control Journal of Mining Science 54(1) 21-26
[4] Amadei B, Stephansson O 1997 Rock Stress and its Measurement (Dordrecht: Springer) p 490
[5] Kaiser J 1953 Erkenntnisse und Folgerungen aus der Messung von Geräuschenbei Zugbeanspruchung von metallischen Werkstoffen Archivfür das Eisenhüttenwesen 24 43-45
[6] Kurita K, Fujii N 1979 Stress memory of crystalline rocks in acoustic emission Geophysical Research Letters 6 9-12
[7] Lehtonen A V, Särkkä P 2006 Evaluation of rock stress estimation by the Kaiser effect In-situ rock stress measurement, interpretation and application: Proceedings of the international symposium on in-situ rock stress (Trondheim, Norway, June 19-21 2006) (London: Taylor & Francis Group) pp 135-142
[8] Momayezy M, Hassani F P 1992 Application of the Kaiser effect to measure in situ stresses in underground mines Proceedings of the 33rd US symposium on rock mechanics (Santa Fe, New Mexico) (Rotterdam: A.A. Balkema) pp 979–987
[9] Seto M, Nag D K, Vutukuri V S 1999 In-situ rock stress measurement from rock cores using the acoustic emission and deformation rate analysis Geotechnical and Geological Engineering 17(3-4) 241-266
[10] Villaescusa E, Seto M, Baird G 2002 Stress measurements from oriented core International Journal of Rock Mechanics and Mining Sciences 39 603-615
[11] Panteleev I A, Mubassarova V A, Zaitsev A V, Karev V I, Kovalenko Yu F, Ustinov K B, Shvetsov N I 2020 The Kaiser effect under multiaxial nonproportional compression of sandstone Doklady Physics 65 396-399
[12] Asanov V A, , Evseev A V, Beltyukov N L 2016 Natural study of marginal array rock's stress state Bulletin of Perm National Research Polytechnic University. Geology. Oil & Gas & Mining 15(20) 270-276
[13] Lord A E, Koerner R M 1985 Field determination of prestress (existing stress) in soil and rock masses using acoustic emission *Journal of Acoustic Emission* 4(2/3) 11-16
[14] McElroy J J, Koerner R M, Lord A E 1985 An acoustic jack to assess in situ rock behavior *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 22 21-29
[15] Toksarov V N, Asanov V A, Evseev A V, Beltyukov N L, Udartsev A A 2016 Sedimentary Rock Stress Determination In Boreholes Using Kaiser Effect *Proceedings of ISRM the 7th International Symposium on In-Situ Rock Stress (Tampere, Finland, 10-12 May 2016)* (Tampere) pp 501-508
[16] Watters R J, Soltani A 1985 Directional acoustic emission activity in response to borehole deformation in rock masses *Journal of Acoustic Emission* 4(1) S17-S18
[17] Baryakh A A, Asanov V A, Pankov I L 2008 Physical and mechanical properties of salt rocks of the Verkhnekamskoe potassium salt deposit (Perm: Perm State Technical University) p 199
[18] Toksarov V N 2000 Experimental determination of stresses in salt rocks: Dissertation abstract, PhD in Technical Sciences (Perm: Mining Institute of the Ural Branch of the Russian Academy of Sciences) p 18
[19] Pankov I L, Morozov I A 2015 The research into friction factor between the ends of specimens of varying heights and press plates on mechanical performance of salt rocks *News of higher educational institutions. Mining Journal* 2 107–113
[20] Fjaer E, Holt R M, Horsrud P, Raen A M, Risnes R 2008 Petroleum related rock mechanics (2nd edition). *Developments in petroleum science* (Amsterdam: Elsevier) 53 p 514
[21] Popp T, Kern H, Schulze O 2001 Evolution of dilatancy and permeability in rock salt during hydrostatic compaction and triaxial deformation *Journal of Geophysical Research* 106(B3) 4061-4078
[22] Schulze O, Popp T, Kern H 2001 Development of damage and permeability in deforming rock salt *Geology* 61 163-180
[23] Costin L S 1983 A microcrack model for the deformation and failure of brittle rock *Journal of Geophysical Research* 88(B11) 9485-9492
[24] Holcomb D J 1993 General theory of the Kaiser effect *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 30(7) 929-935
[25] Li C, Nordlund E 1993 Experimental verification of the Kaiser effect in rocks *Rock Mechanics and Rock Engineering* 26(4) 333-351
[26] Pestman B J, van Munster J G 1996 An acoustic emission study of damage development and stress-memory effects in sandstone *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 33(6) 585-593
[27] Hsieh A, Dight P 2016 The desirable and undesirable effects on stress reconstruction using the deformation rate analysis (DRA) *Proceedings of ISRM the 7th International Symposium on In-Situ Rock Stress (Tampere, Finland, 10-12 May 2016)* (Tampere) pp 213-223