2008/2 vol.5

ACTA GEOTECHNICA SLOVENICA

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ISSN 1854-0171

ACTA GEOTECHNICA SLOVENICA

ISSN: 1854-0171

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500 izvodov - issues

tisk | **print**

Tercia tisk d.o.o. Ptuj

Revija redno izhaja dvakrat letno. Članki v reviji so recenzirani s strani priznanih mednarodnih strokovnjakov. Baze podatkov v katerih je revija indeksirana: SCIE - Science Citation Index Expanded, JCR – Journal Citation Reports / Science Edition, ICONDA - The international Construction database, GeoRef
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The journal is published twice a year. Papers are peer reviewed by renowned international experts. Indexation data bases of the journal: SCIE - Science Citation Index Expanded, JCR – Journal Citation Reports / Science Edition, ICONDA - The international Construction database, GeoRef
Financially supported also by Slovenian Research Agency.

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UVODNIK

Pričujoča številka revije Acta Geotechnica Slovenica prinaša pet prispevkov, ki so za bralce zelo zanimivi in obravnavajo tako temeljna znanja kot inovativnosti iz praktičnih primerov.

Avtorja prvega članka S. Bensehamdi in A. Seriani obravnavata interakcijski vpliv stropne, podporne in talne konstrukcije na celotno stabilnost rudnika. Rezultati numeričnih analiz jasno kažejo, da modeli z linearnimi končnimi elementi ne prikazujejo realnega obnašanja rudarske konstrukcije. Vseeno pa z njimi dobimo nazorni prikaz omejitev rešitev z linearnimi končnimi elementi pri opisovanju dejanskega obnašanja rudarske konstrukcije, še posebej za relativno mehko kamninsko maso, za katero je dokazana uporabnost nelinearnega modela.

J. Likar in sodelavci so v drugem prispevku prikazali rezultate in analize mikroseizmičnih meritev v območju premogovnika Velenje. Meritve tresljajev tal v okolici rudnika so se izvajale zaradi pritožb prebivalcev bližnjih naselij.

Naslednji trije članki so rezultat delovanja raziskovalnih skupin, ki so v letih 2005 do 2007, v okviru Srednjeevropske mreže odličnosti za vodo, sodelovale v projektni mreži *Water resources and their management*. V okviru te projektne mreže je v Sloveniji potekalo kar šest projektov v sodelovanju z različnimi gospodarskimi družbami in tujimi raziskovalnimi inštitucijami. Zaradi izredno zanimive tematike teh projektov, bomo z objavljanjem njihovih inovativnih rezultatov nadaljevali tudi v naslednjih številkah.

Prispevek avtorice B. Dolinar in sodelavcev obravnava problem sedimentacije lebdečih plavin v pretočnih akumulacijskih jezerih hidroelektrarn na rekah. Cilj opisanih raziskav, ki se nanašajo na akumulacijsko jezero hidroelektrarne Boštanj na reki Savi, je bil ugotoviti vrsto in količino sedimentiranega materiala v jezeru v izbranem časovnem obdobju. V ta namen je bila preiskana mineralna in kemična sestava ter koncentracija in velikost suspendiranih delcev pri vtoku vode v jezero in ob njenem iztoku.

Članek H. Vrecl-Kojc in sodelavcev prikazuje analizo procesa sedimentacije suspendiranega materiala v akumulacijskih jezerih, ki temelji na interakciji med sedimentacijsko hitrostjo in gibanjem vode v jezerih z visokimi dnevnimi oscilacijami. Sedimentacijska hitrost grobih sferičnih delcev je v prisotnosti sile vzgona funkcija velikosti sedimenta. Gibanje vode v rezervoarju je analizirano s tridimenzionalnim modeliranjem tekočinskih tokov. Ocenitev rezultatov je prikazana za primer planirane črpalne hidroelektrarne »Kozjak« na reki Dravi.

M. Pobrežnik in sodelavci predstavljajo v zadnjem članku razvoj sodobne metode za izboljšanje kakovosti podzemne vode z ekonomsko perspektivno uporabo ogljikovega dioksida. Optimalna količina ogljikovega dioksida, ki je naravna komponenta podzemne vode, ob uporabi le-te v različne namene nudi hkrati zaščito pred odlaganjem mineralnih oblog in preprečuje korozijo.

Ludvik Trauner
Glavni urednik

EDITORIAL

This issue of the journal Acta Geotechnica Slovenica brings together five articles that cover fundamental knowledge as well as innovations in terms of practical examples, all of which should be of great interest to our readers.

The authors of the first paper, S. Bensehamdi and A. Seriani, deal with the effects of the interaction of roof, pillar and floor on the overall stability limit of a mine. The numerical results clearly show that finite-element linear models cannot realistically represent the true behaviour of the mine's structure. However, they certainly demonstrate the limitations of the finite-element linear solutions when it comes to representing the true behaviour of the mine's structure, particularly when the rock-mass structure is relatively weak, which means that a non-linear approach is justified.

In the second paper, J. Likar and colleagues show the results and analyses of micro-seismic measurements in the area of the Velenje mine. The measurements of ground vibrations were carried out in response to the complaints of people living in nearby settlements.

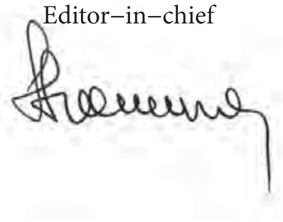
The next three papers include results from research groups that took part in the project network *Water resources and their management* within the Middle-European Network of Excellence for Water in the years 2005 to 2007. In Slovenia, there were six projects in the frame of this project network in cooperation with various companies and foreign research institutions. Because of the very interesting topics covered by all of these projects, the publication of their results will be continued in the forthcoming issues.

The paper by B. Dolinar and her colleagues concentrates on the problem of the sedimentation of the suspended load in the water-storage reservoirs of hydroelectric power plants. The objective of the described studies was to determine the quantity and type of deposited material in the reservoir during the selected time period. For this purpose, the mineral and chemical compositions as well as the concentration and the particle size of the suspended load were examined at the intake and outflow of the water entering and leaving the water-storage reservoir of the hydroelectric power plant Boštanj on the River Sava.

The paper of H. Vrecl-Kojc and her colleagues presents an analysis of the suspended-load sedimentation process in the water-storage reservoirs based on the interaction between the sedimentation, i.e., the settling, velocity and the motion of the water in the reservoirs with high daily oscillations. The settling velocity of spherical particles in the presence of a buoyancy force is a function of the particle size. The motion of the water in the reservoirs is analyzed by the three-dimensional modelling of liquid streams. The evaluation of the results is presented for the case of the planned Kozjak pumping hydroelectric power plant on the River Drava.

In the last paper, M. Pobrežnik and colleagues present the development of a modern method for improving the quality of underground water by the application of carbon dioxide. The optimal content of carbon dioxide, which is a natural component in underground water and is used in urban areas for different purposes (e.g., drinking water, heating systems), provides protection from the precipitation of mineral deposits and prevents corrosion.

Ludvik Trauner
Editor–in–chief



MODELIRANJE PODPIRANJA RUDARSKIH IZKOPOV Z NELINEARNIMI KONČNIMI ELEMENTI Z UPOŠTEVANJEM DEFORMACIJSKEGA MEHČANJA KAMNINSKE MASE

SALIM BENSEHAMDI in ABDELBAKI SERIANI

o avtorjih

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izvleček

Za simulacijo obnašanja kamninske mase in razvoj con popuščanja v območju podpiranja rudarskih izkopov je bil uporabljen dvodimenzionalen model, ki upošteva kriterij po porušitvi. Model upošteva deformacijsko mehčanje kamninske mase in njeno residualno trdnost – trdnost po porušitvi. Analiza stabilnosti konstrukcije upošteva glavne značilnosti popuščanja rudarske konstrukcije zaradi obtežbe in posledičnega spreminjanja togosti kamninske mase ter nadaljnji razvoj napetosti. Izvedene so bile obsežne parametrične analize, v katerih je bil raziskan interakcijski vpliv stropne, podporne in talne konstrukcije na celotno stabilnost rudnika. Rezultati numeričnih analiz jasno kažejo, da modeli z linearnimi končnimi elementi ne prikazujejo realnega obnašanja rudarske konstrukcije. Vseeno pa z njimi dobimo nazorni prikaz omejitev rešitev z linearnimi končnimi elementi pri opisovanju dejanskega obnašanja rudarske konstrukcije, še posebej za relativno mehko kamninsko maso za katero je dokazana uporabnost nelinearnega modela.

ključne besede

analiza z nelinearnimi končnimi elementi, popuščanje, cone plastičnosti, komorno/steberna odkopna metoda, rezidualna trdnost

NON-LINEAR FINITE-ELEMENT MODELLING OF ROOM AND PILLAR MINE WORKINGS INCLUDING THE STRAIN-SOFTENING BEHAVIOUR OF THE ROCK MASS

SALIM BENSEHAMDI and ABDELBAKI SERIANI

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Abstract

A two-dimensional model adopting post-failure criteria was used to simulate the behaviour of the rock mass and the development of yield zones around room and pillar mine workings. The model conformed to the strain-softening behaviour of the rock mass and accounted for its post-failure residual strength. The structural-stability-analysis approach accounted for the main features of the mine structures' yield produced during loading through changes in the rock material's stiffness and the subsequent evolution of the stresses. A comprehensive parametric analysis was performed and the inevitable effect of the interaction of the roof, pillar and floor on the overall stability limit of the mine was investigated. The numerical results clearly showed that the finite-element linear models could not realistically represent the true behaviour of the mine structure. However, they clearly demonstrated the limitations of the finite-element linear solutions in representing the true behaviour of the mine structure, particularly when the rock-mass structure is relatively weak, and that a non-linear approach was justified.

Keywords

non-linear FE analysis, yielding, plastic zones, room and pillar mining, residual strenght, stability assessment

1 INTRODUCTION

One of the most difficult design problems in practical rock mechanics arises in conditions of the rock mass's complex non-linear constitutive behaviour, including structural discontinuities, and the non-homogeneity of the medium [7]. Field measurements and laboratory tests have shown the presence of the strain-weakening behaviour of the rock mass and have indicated that in many cases the assumption that the rock is linearly elastic leads to calculated stresses and displacements that disagree significantly with the measured values. In particular, as the rock mass around an excavation may exist in the post-yield state [2], [3], a realistic approach should incorporate the effect of the post-yield behaviour in the analysis [5], [10]. In the current finite-element analysis this has usually been achieved by adopting an elastic, perfectly plastic model and gradually changing the material coefficients of the yielding materials using a quasi-elastic finite-element solution [4]. In this paper an advanced elastic-plastic LUSAS finite-element program [6] was used to predict the distribution of stresses during the plastic and elastic strain states, and to simulate the possible mechanisms of the yield of the rock mass around a mine opening. This accounted for the residual strength after the failure.

2 DESCRIPTION OF THE MATERIAL MODEL

The solutions of existing non-linear material models that are used to simulate rock mechanics and other geotechnical problems are somewhat limited in their ability to properly reflect the behaviour of the complete stress-strain curve of most rock materials. [5] Both laboratory and field measurements have indicated that immediately after the peak strength level is reached, the stress-strain curve drops with a negative gradient and then flattens out at a residual strength. The classical solution adopting the constant-load incremental technique has been shown to fail when the solution reaches the limit points on the material stress-strain curve, as shown in Fig. 1 and Fig. 2, [4], where either load- or displacement reversal occurs, resulting in a singular stiffness matrix, which automatically leads to the failure of the solution to converge. The LUSAS finite-element programs [6] used in this analysis contain a model that allows a simulation of the material's behaviour well into the strain-softening part of the stress-strain curve.

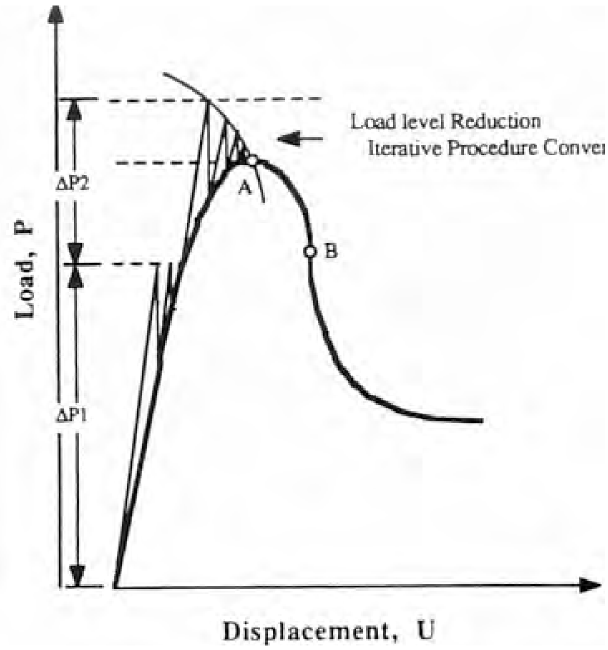


Figure 1. LUSAS modified arc length incrementation solution.

A general method that may follow the solution path through the well-known post-peak portion of the material's stress-strain curve is the modified arc-length technique [1]. The salient characteristic of the arc-length technique is that the load level does not remain constant at each load increment, where during each iteration the load level is modified so that convergence near the limit points A and B can be achieved, Fig. 1. A typical, modelled, material stress-strain characteristic is illustrated in Fig. 2, where the complete stress-strain curve of the tested rock material is matched by a series of elastic and plastic lines, K_0, K_1, and K_n, corresponding to the material's performance in the elastic and plastic states [5].

The initial portion of the model, as matched by the plastic line k_1, represents the work-hardening behaviour of the material, which is characterized by increasing stress with plastic deformation, while the second portion of the model shows the behaviour of the strain-softening state of the material, having a residual strength that decreases with plastic deformation, and finally an ideally plastic state of the material, where the deformation increases at constant stress.

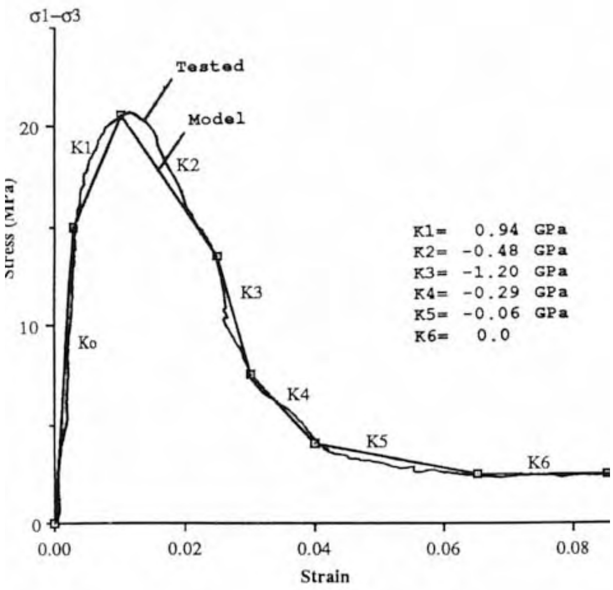


Figure 2. Modelled material stress-strain curve.

3 CONSTITUTIVE LAW

In the elastic range, the way in which the stress and the strain are related for a material under load is described qualitatively by its constitutive behaviour. For an isotropic body undergoing plane-strain deformation, the stress-strain relation follows Hooke's law Eq. (1), that is:

$$\{\sigma\}_e = [E]_e \{\varepsilon\}_e$$

$$\{\sigma\}_e = \begin{vmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{vmatrix}, \{\varepsilon\}_e = \begin{vmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{vmatrix} \qquad (1)$$

$$[E]_e = \frac{(1-\nu)}{(1+\nu)(1-2\nu)} \begin{vmatrix} 1 & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & 1 & 0 \\ 0 & 0 & \frac{1-2\nu}{2(1-\nu)} \end{vmatrix}$$

For non-linear material behaviour the plastic state is specified by:

1. A yield function to specify the onset of plastic deformation, Eq. (2):

$$F(\{\sigma\},|K|)=0 \qquad (2)$$

where

F: Yield function

$\{\sigma\}$: Stress vector

$|K|$: Hardening, softening parameter

In classical plasticity, stress states that provide a positive value of the yield function cannot exist. However, in numerical models, positive values of the yield function indicate that yielding should occur and the stress state is modified by accumulating plastic strains until the yield criterion is reduced to zero. This process is known as the plastic-corrector phase or return mapping.

2. A flow rule to define the plastic straining is given by Eq. (3):

$$\delta\{\varepsilon\}_{P} = \lambda \frac{\partial F}{\partial\{\sigma\}} \qquad (3)$$

where

$\delta\{\varepsilon\}_P$: Increment vector of the plastic strain

$\frac{\partial F}{\partial\{\sigma\}}$: Direction of the plastic strain

λ: Lagrangian plastic multiplier defining the magnitude of the plastic strain

3. A hardening and softening rule to define the evolution of the yield surface with plastic strain. This is defined by describing the evolution of the yield function in relation to the effective plastic strain, ε_{effp}, using a series of straight-line segments, Fig.2.

$$K_{effp} = \sigma_y + |K_n|.\varepsilon_{effp} \qquad (4)$$

where

K_{effp}: Effective hardening, softening slope

σ_Y: Initial yield stress

$|K_n|$: Hardening, softening slopes

During an increment of stress, $\delta(\sigma)$, changes in the strain are assumed to be the sum of an elastic and a plastic component. Thus, the concept of total strain will be invoked, Eq. (5):

$$\delta\{\varepsilon\} = \delta\{\varepsilon\}_e + \delta\{\varepsilon\}_p \qquad (5)$$

The elastic strain components, $\delta(\varepsilon)_e$, are related to the stress components by a matrix of constant [E], known as the stiffness matrix Eq. (6):

$$\delta\{\varepsilon\}_e = [E]^{-1}.\delta\{\varepsilon\} \qquad (6)$$

Taking account of the elastic and plastic components produces Eq. (7):

$$\delta\{\varepsilon\}_e = [E]^{-1}.\delta\{\varepsilon\} + \lambda \frac{\partial F}{\partial\{\sigma\}} \qquad (7)$$

The elastic-plastic stress and strain increments may be related by the following equation. Eq. (8):

$$\delta\{\varepsilon\}_e = [E]_{ep}.\delta\{\varepsilon\} \qquad (8)$$

where

$[E]_{ep}$ is the elasto-plastic stiffness matrix

During the elastic-plastic analysis, the material's stiffness matrix is updated by the new, computed elastic-plastic stiffness matrix, $[E]_{ep}$, at each increment of the finite-element solution [2], [3].

4 THE NON-LINEAR FINITE-ELEMENT TECHNIQUE

The technique for performing a non-linear finite-element analysis is illustrated in Fig. 3 (next page).

This technique is summarized as follows:

1) First, load increments are applied to the mine structure and the strains and hence the stresses are found at the Gaussian points in the elements. For each increment of load, an initial material stiffness is used and the elastic solution is obtained.

2) During the solution the courses of all the finite elements are checked for yield. If the stresses at the Gaussian points lie within the previously prescribed yield surface, the stress update has been completed. Otherwise, stress lying outside the yield surface must be returned to the yield surface by plastic straining. During each iteration cycle, computed stresses and strains are added to the total already accumulated and a new material-stiffness matrix is reformulated for the next load increment. Within each load increment the system of Eq. (9):

$$\delta\{\sigma\}_i = [E]_{iep}.\delta\{\varepsilon\}_i \qquad (9)$$

must be solved for the strain increment $\delta\{\varepsilon\}_i$

where

$\delta\{\sigma\}i$: Increment of stress during iteration, i

$[E]_{iep}$: Updated elasto-plastic stiffness matrix

$\delta\{\varepsilon\}_i$: Strain increment during iteration

$\delta\{\varepsilon\}_i = \left(\delta\{\varepsilon\}_e + \delta\{\varepsilon\}_p\right)$

3) Steps (1) and (2) are repeated for all the increments of load that constitute the total load applied to the structure.

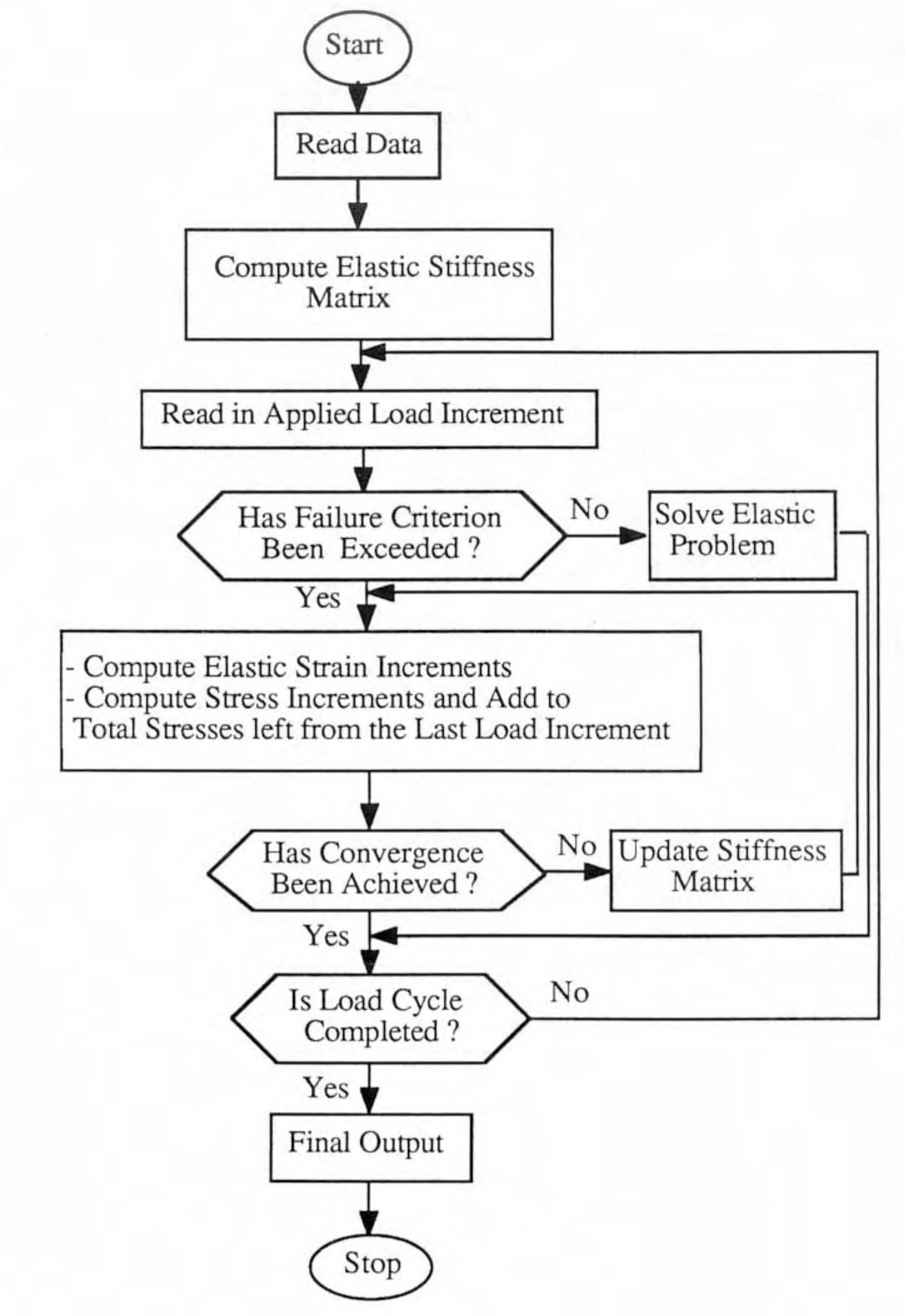


Figure 3. Simplified plasticity-solution flow diagram.

5 TWO-DIMENSIONAL FINITE-ELEMENT ANALYSIS OF ROOM AND PILLAR MINING

5.1 BOUNDARY CONDITION OF THE PROBLEM

A two-dimensional finite-element model under plane strain of a typical room and pillar mine working is illustrated in Fig. 4.

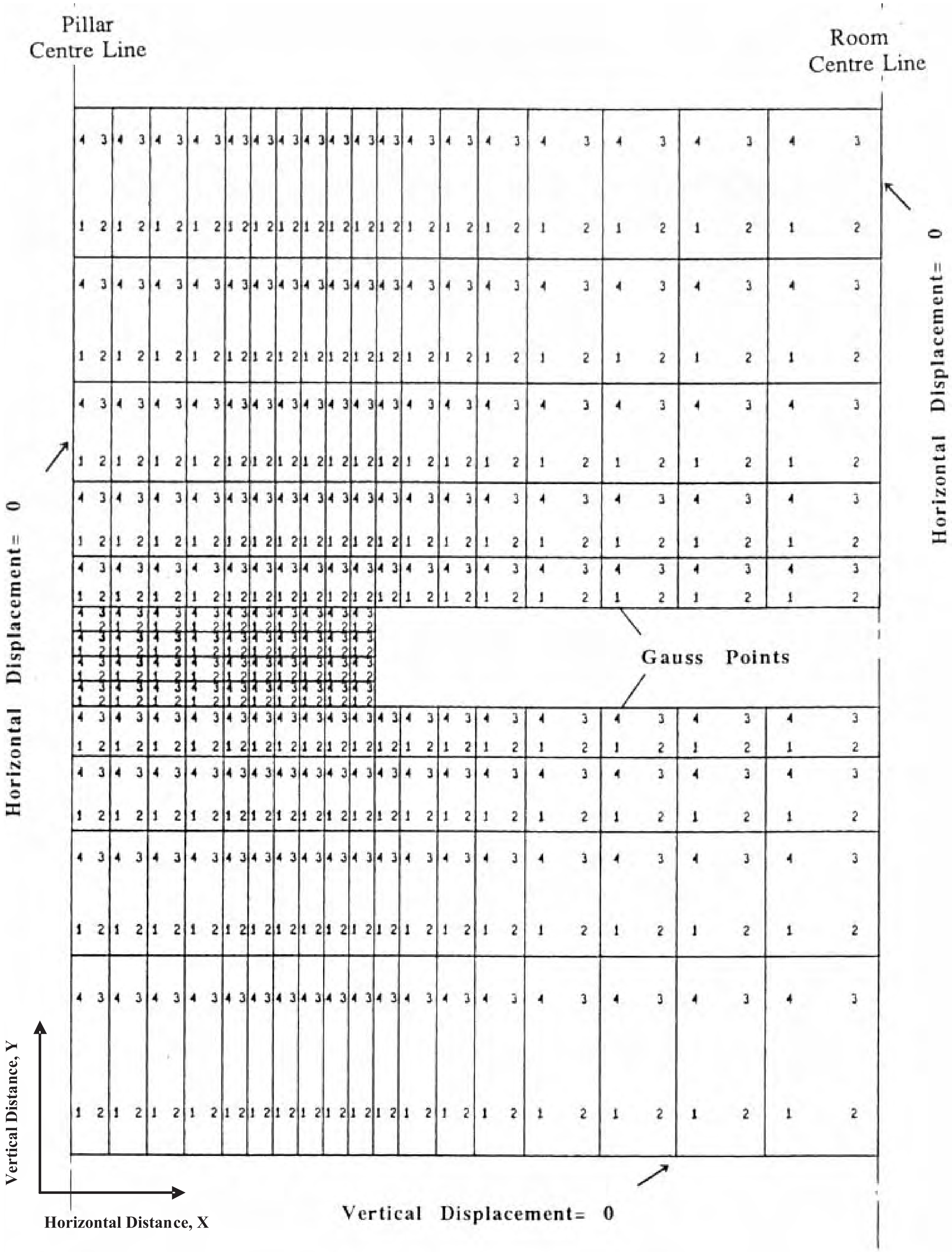


Figure 4. Typical finite-element mesh of room and pillar mining configuration of vertical cross-section with boundary conditions.

The model consists of 202 four-noded isoparametric elements. Since the mesh of the model was symmetrical, only half of the configuration was considered. Lateral movement in the X direction of the model was prevented on its sides, allowing only vertical movement in the Y direction to occur. The nodal points corresponding to the lower strata of the floor were held fixed in both directions. The model enabled different mining configurations to be simulated with various properties, as well as the stress-strain behaviour to be assigned to the roof, pillar, and floor, Table. 1

point is readjusted and the elements' post-yield stiffness is updated according to the criterion of the stress and strain-softening laws, respectively. The stress around the entry is then redistributed and shifted to the unyielding or stiffer parts of the structure, as the surrounding rock mass seeks the final equilibrium steady state under a given overburdened load and mining sequence.

The structural stability analysis is first focused on the assessment of the overall stability of the support pillars in terms of the maximum yield that occurs throughout

Table 1. Physical and mechanical properties of the model strata.

Model strata sequence	Material type	Young's modulus E, MPa	Unit Weight γ, Kg/m^3	Poisson's ratio υ	Uniaxial Compressive Strength, σ_c, MPa	Shear strength τ_c, MPa	Friction Angle φ, (°)
Roof	Marl - Limestone	20000	2550	0.20	20.0	7.0	45
Immediate roof	Marl	3000	2600	0.35	12.0	2.0	35
Pillar	Coal	3600	2500	0.35	20.6	0.5	33
Immediate floor	Organic Marl	3300	2500	0.40	2.8	1.8	30
Floor	Limestone	15000	2500	0.25	35.0	6.0	34

5.2 FINITE-ELEMENT METHOD

Quite frequently, the only information required from the designer is that of determining the mine-structure collapse situation. It has been shown that under stiff loading, the progressive failure of rocks in compression is associated with a decrease in strength through accumulated plastic deformation and fracture. The inelastic post-yield characteristics of the rock strata are the major variables that characterize the mechanical behaviour of the yielded rock material in the post-failure state. The relationship between post-failure strength and stiffness is established according to a given material failure criterion and is used to simulate the growth of the yield zone surrounding a mine opening and hence to assess its overall stability.

In the following structural stability analysis of room and pillar mine workings a non-linear finite-element analysis is performed, adopting the Mohr-Coulomb yield criteria. The model simulates the behaviour of a mine structure in two stages: an elastic state prior to yielding, followed by a plastic state for the strain-weakening behaviour of the rock material. The plastic incremental analysis takes into consideration the degree of local yielding that occurs around the mine opening. Through a series of successive computer runs, all the Gaussian points are checked against failure, and if any violation of the stress criterion is detected then the stress state at the Gaussian

the pillar's cross-section [8], [9]. The extent and development of the yield zone through the pillar's width can be compared to the remaining elastic core of the effective support that the pillar still retains after yield. Under small loads, only a minor yield portion of the pillar rib develops.

However, if the pillar is loaded to such a degree that the yield zone extends throughout the whole cross-section of the pillar, then the oveall instability of the pillar occurs.

6 RESULTS OF THE FINITE-ELEMENT ANALYSES

A series of elastic-plastic finite-element runs was first performed under plain-strain conditions for the purpose of estimating the changes to, and location of, the peak abutment stress in the pillar as it yields progressively under loading. Fig. 5 shows the evolution of the finite-element-computed vertical stress component stresses for a complete loading cycle under plastic conditions, compared to the computed vertical stress components that could have arisen under purely elastic conditions. The total load on the pillar was initially applied in small increments so as to simulate the behaviour of a pillar during the transition from the elastic to the plastic state. As the load is applied, the pillar progresses through two

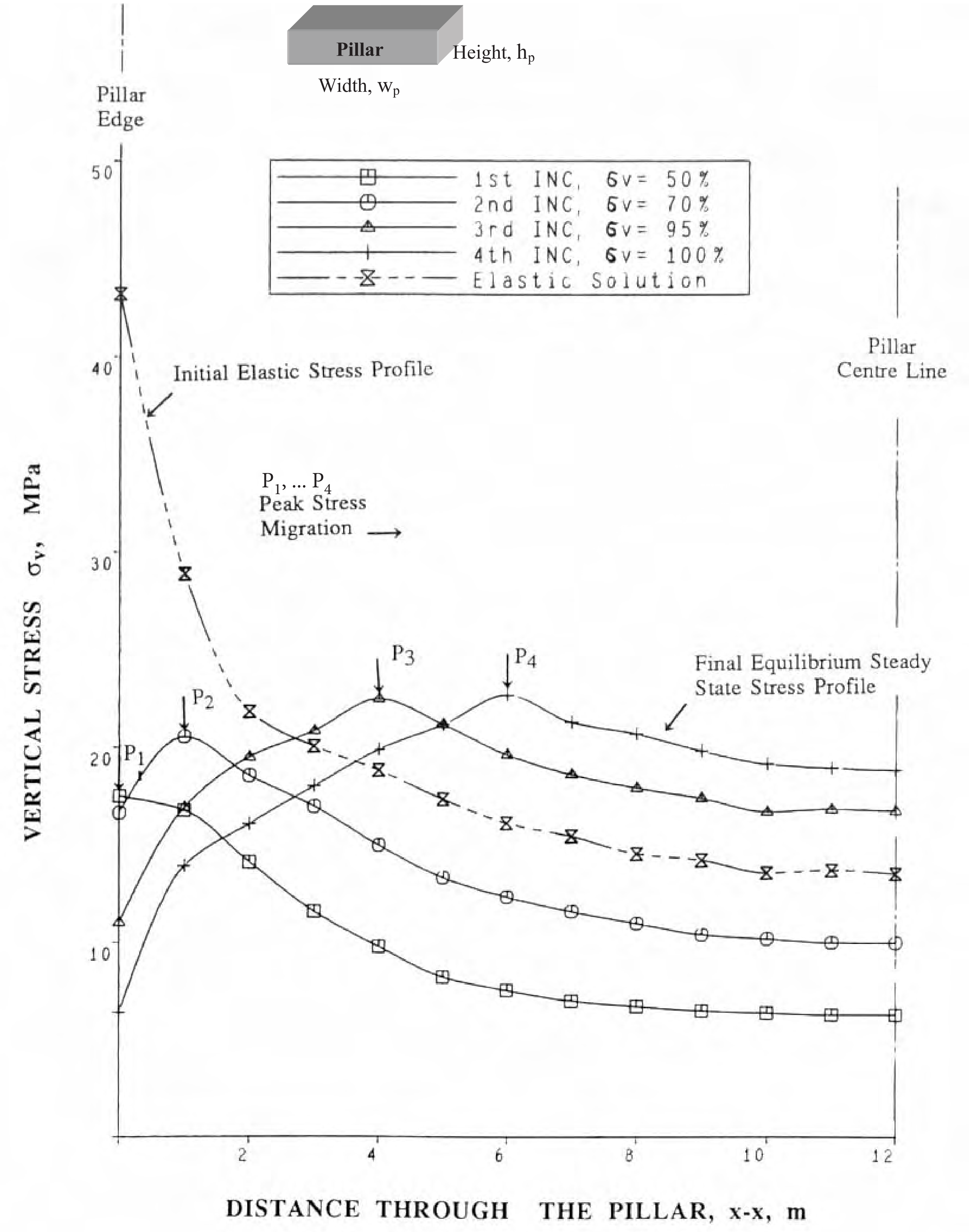


Figure 5. Change in the vertical stress profile in a yielding support pillar, extraction ratio r = 60%, w_p/h_p = 6.0.

distinct stages: an elastic deformation and yield work hardening, which is maintained up to the pillar material's bearing strength of 20.6 MPa, Fig. 2, and the collapse of the mine structure, which is represented by yield work softening. During the yielding process, the pillar material loses its bearing strength, with the excess of the stress being absorbed by the plastic deformation. The peak load built up on the pillar $P_1, \dots P_n$, Fig. 5, is then shifted towards the pillar core as the yield progresses. However, the yielded parts of the pillar still develop some bearing strength, but this depends on the post-yield material's properties, the magnitude of the applied load and the distance from the previously yielded part of the pillar. A good representation of this stress-change phenomenon is clearly illustrated in Fig. 5, where a significant difference in the vertical stress prediction

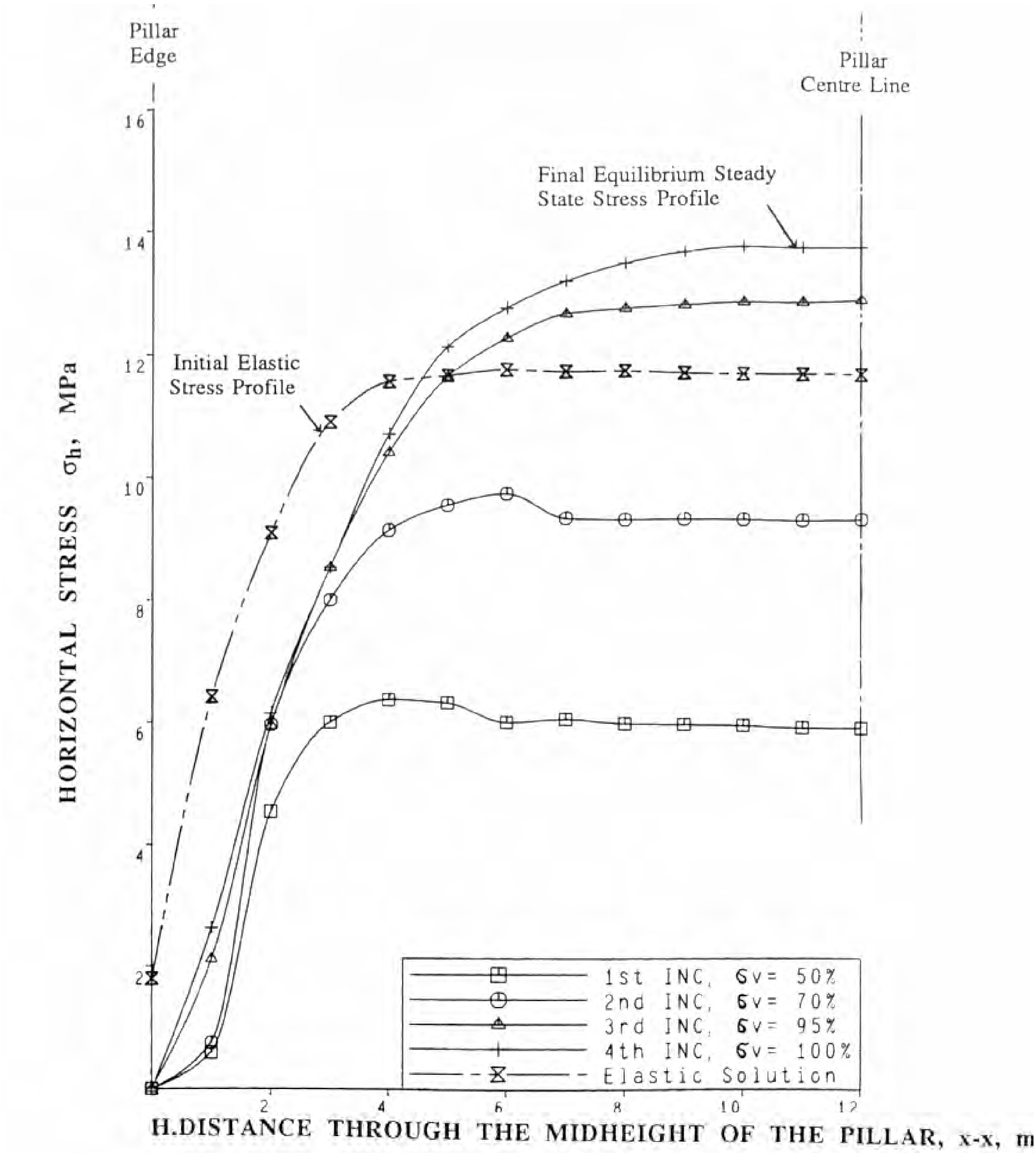


Figure 6. Change in the horizontal stress profile in a yielding support pillar, extraction ratio r = 60%, w_p/h_p = 6.0.

has been found when compared to the final steady-state stress profile predicted from the plastic solution and that predicted from the elastic one.

The induced horizontal stress components at the mid-height of the pillar for various increments of the applied load are given in Fig. 6, where theses stress components are seen to increase from zero at the pillar edge to a maximum value at the centre of the pillar.

Vertical and horizontal stress contour plots for yielding roof, pillar and floor are given in Fig. 7.

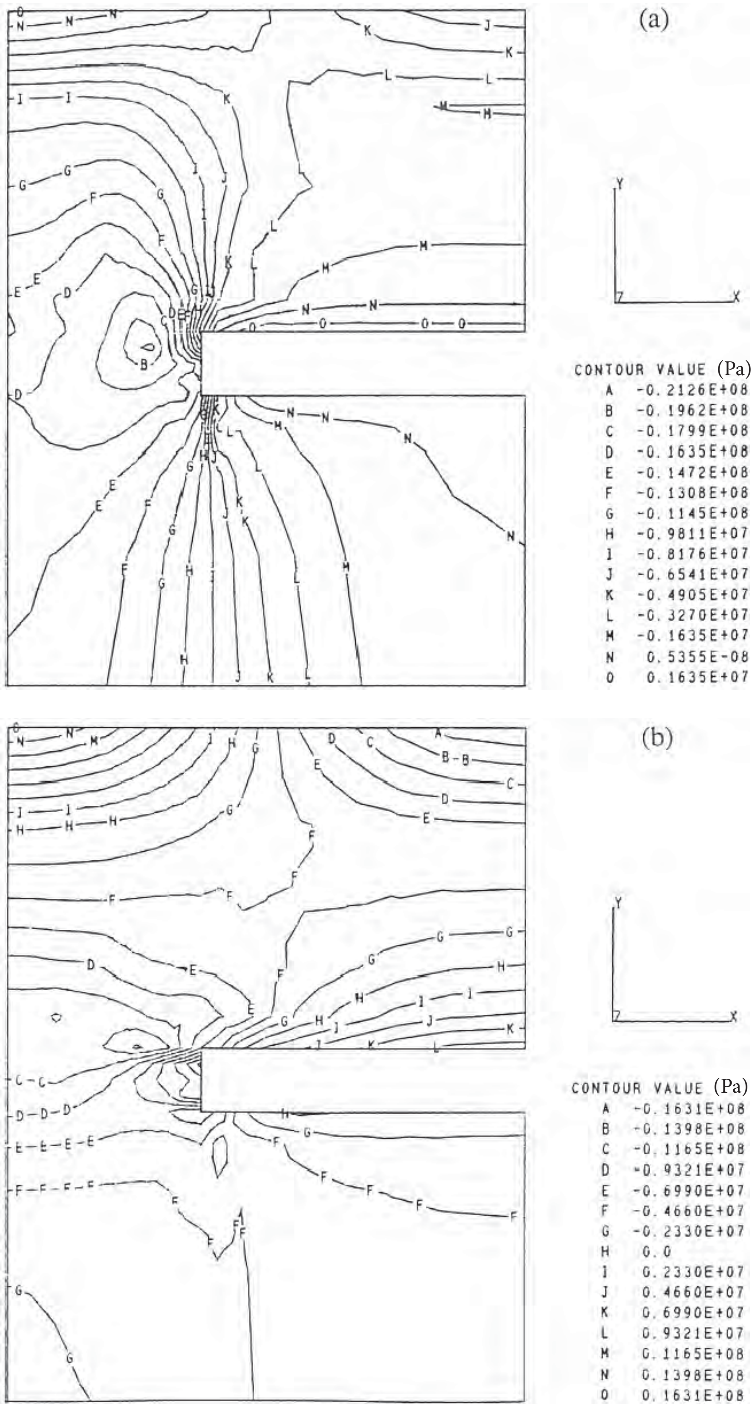


Figure 7. Vertical and horizontal principal stress contours, a and b, in a yielding room and pillar mine structure at the final equilibrium steady state.

The plots provide an excellent picture of the final state of the induced stresses of the yielding mine structure, which shows stress-relief zones around the pillar corners and some distance into the mine structure, where the peak stress is built up.

The shear-stress contours given in Fig. 8b show a shear-stress concentration at the roof-pillar intersection given by an elastic FE solution, while in Fig. 8a the shear stress is seen to be much lower in this area, and the reduced peak shear stress is shifted vertically in the roof.

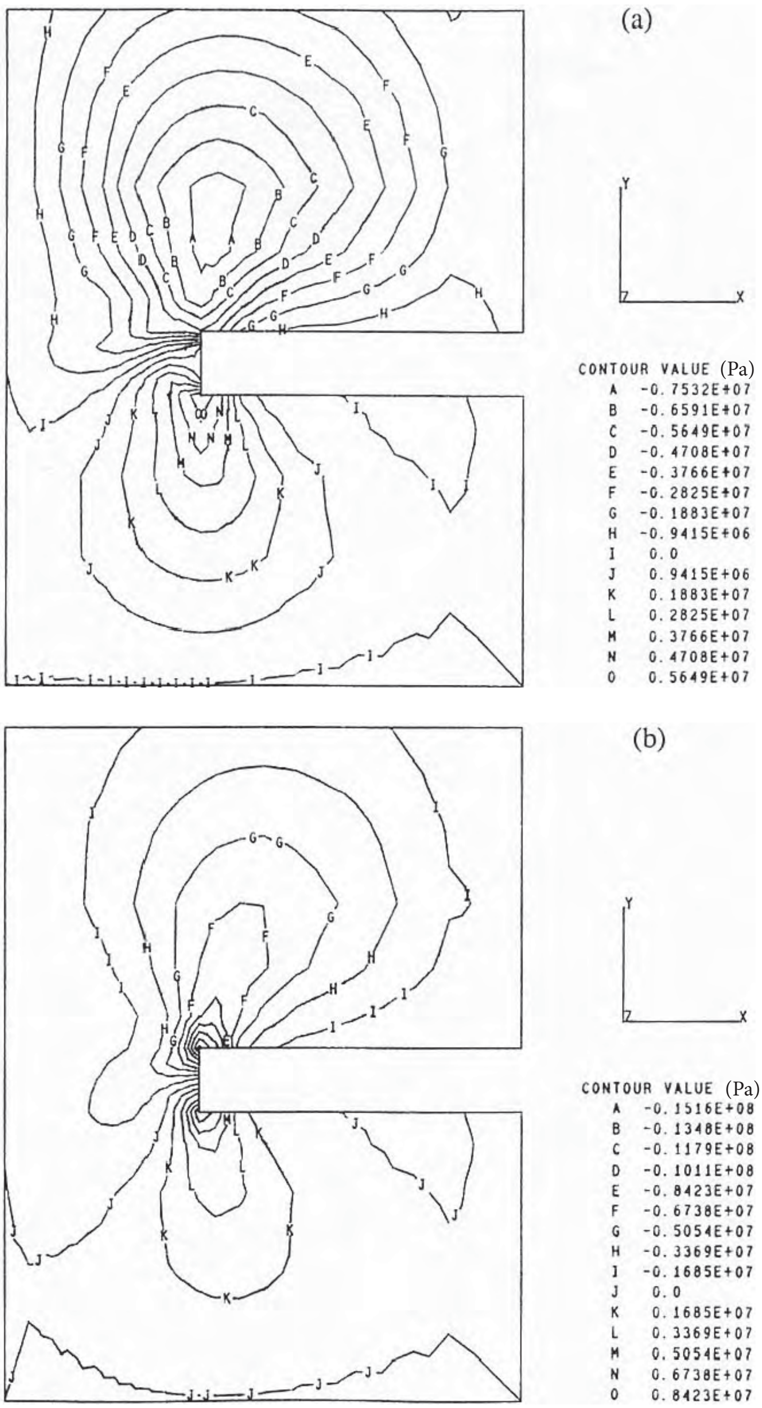
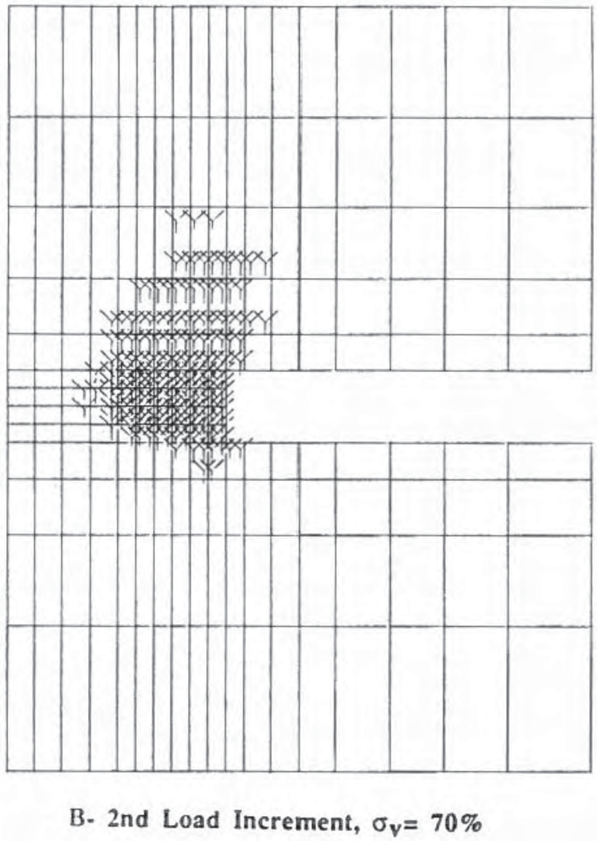


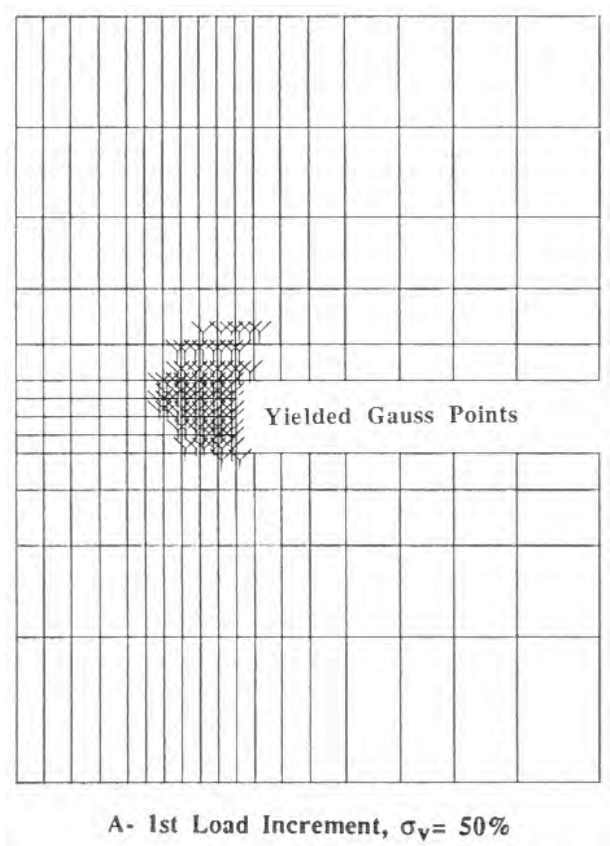
Figure 8. Shear-stress contours in a yielding plastic FE solution (a), and unyielded elastic FE solution (b), of a room and pillar mine structure at the final equilibrium steady state.

A relationship exists between the yield deformations of the pillar, where three distinct stress zones develop as the pillar is yielding:

- A zone of local yielding in a stress-relieved area,
- A zone of transition from a yielding to the solid state in the pillar, where the stress -concentration area was developed,
- A zone of pillar core that has a uniform confined stress.

The overall pillar stability depends upon the geometrical development of these principal zones. For example, an increase in the yielding pillar area results in a decrease of the solid core, and hence a decrease in its bearing performance, which automatically leads to the instability of the system. Fig. 9 shows the yielding state of the mine structure where the growth of the plastic zone for each load increment is given by the yield Gaussian points. At 50% of the maximum applied load, Fig. 9A, the first plastic zones are shown to occur at the immediate roof-pillar intersection, over the cross-section of the pillar and, to a limited extent, at the floor-pillar intersection. In this case the solid pillar area is over 50% of the total





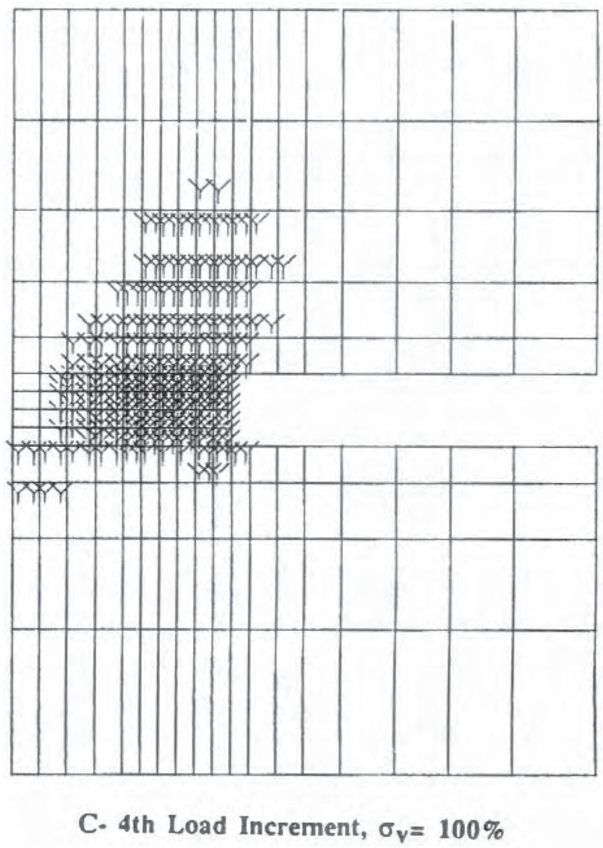
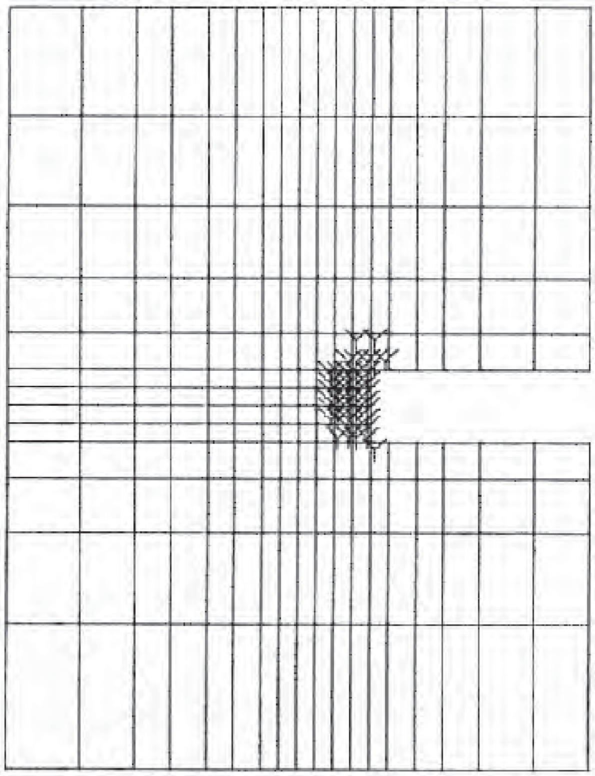


Figure 9. Spread of the yield zone at various applied load levels; the extraction ratio r = 60%.

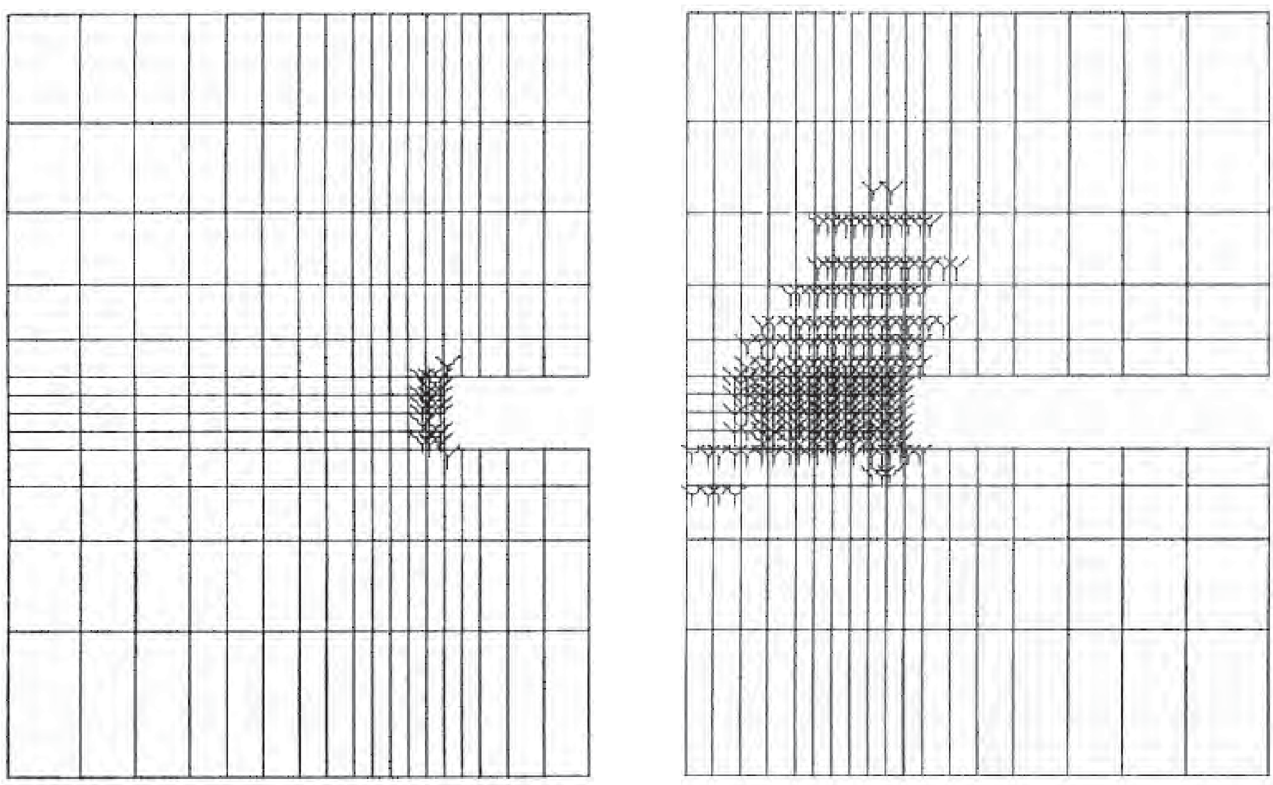
area, and the pillar is assumed to be stable. As the load is increased, the plastic zone spreads upwards into the immediate roof and laterally into the pillar, Fig. 9B. The effective pillar core is reduced to less than half of the pillar area, but can still provide support. At the final stage of loading, the yielded zone reaches its maximum as the mine structure passes to its final equilibrium steady state, as shown in Fig. 9C, where the plastic zone is seen to increase considerably in both the roof and the pillar, while the floor remains almost unaffected. The effective pillar area is reduced to more than half of the total pillar area and overall pillar instability is likely.

At low extraction ratios of 0.25 and 0.40, as shown in Fig. 10 (A, B), the developed yield zone is confined to an area around the rock-mass opening interface. In both cases the area of effective support is shown to be larger than the outer yield zone. Under these conditions, the pillar is almost at its maximum capability and the mine structure is stable.

The non-linear finite-element analysis was further extended to analyse the influence of the roof, pillar and floor interactions on the overall pillar stability. In order



B- Ext. Ratio= 40%



A- Ext. Ratio= 25%

C- Ext. Ratio= 60%

Figure 10. Spread of the yield zone at the full applied load level and various extraction ratios, *r*.

to find out the effect of this interaction as well as the effect of the change of their properties on the overall pillar stability, three models were analysed using different properties for the roof, pillar and floor. Fig. 11 shows the predicted vertical and horizontal stresses of the pillar for model A, having a stiff roof, a weak pillar and a weak floor; and model B, having a weak roof, a weak pillar and a stiff floor; and model C, where the roof and the floor are taken to be stiff and the pillar is kept weak.

It is clear from Fig. 12 (next page) that for the same pillar material in the three suggested models and the different combinations of material properties for the roof and floor, model C shows complete yielding of the pillar, while in model B the area of effective support is considerably reduced, but to a lesser extent than with model C. Finally, in model A, a moderate effective area is indicated in the pillar, which yields to a certain degree. It can be concluded from these findings that the interaction of the roof, pillar and floor has a significant effect on the pillar's overall stability. Therefore, when assessing the stability of a given room and the pillar mine workings, the roof, pillar and floor should be considered as an integrated structure. This approach generally yields more accurate results.

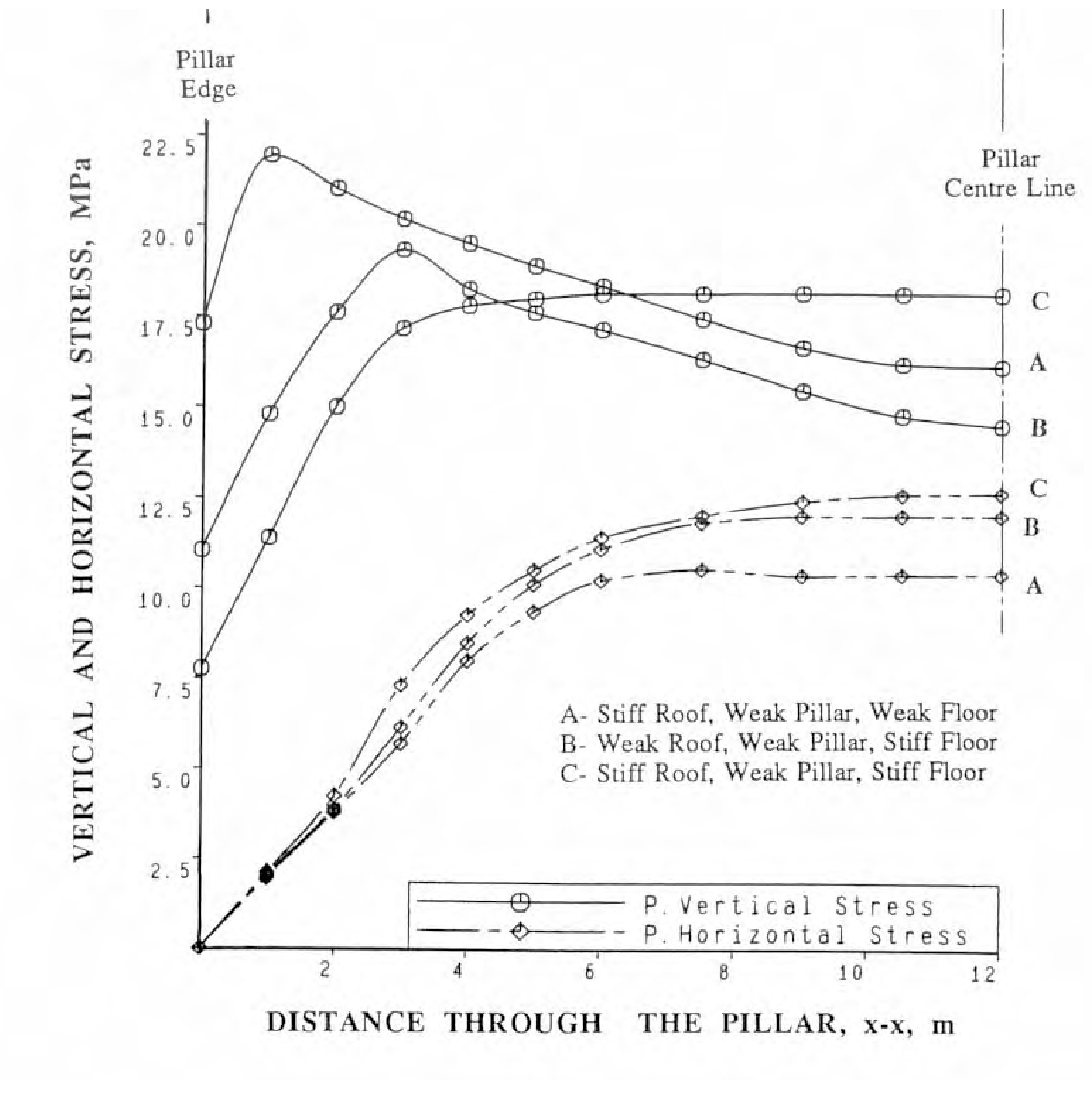
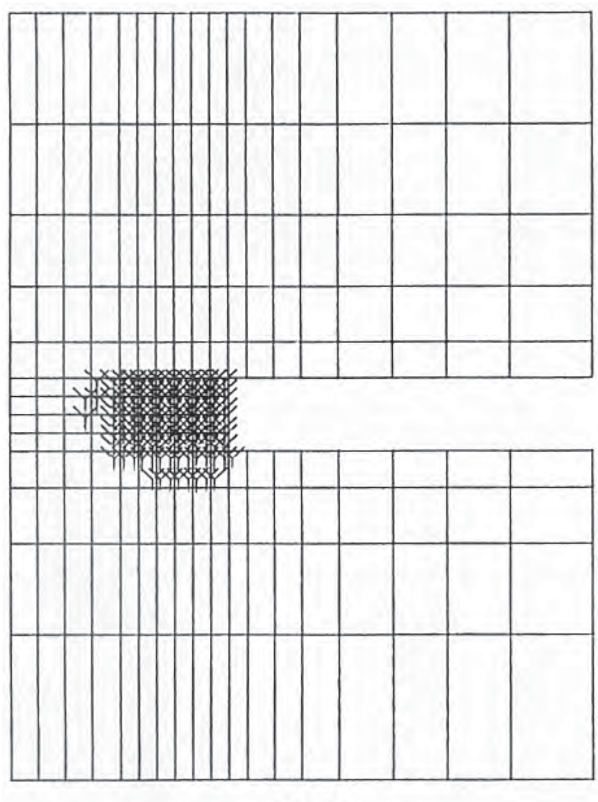
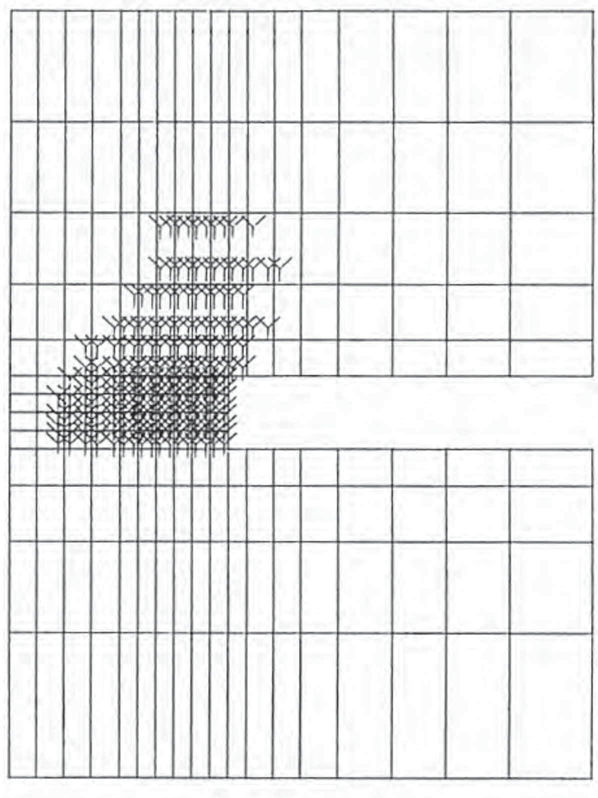


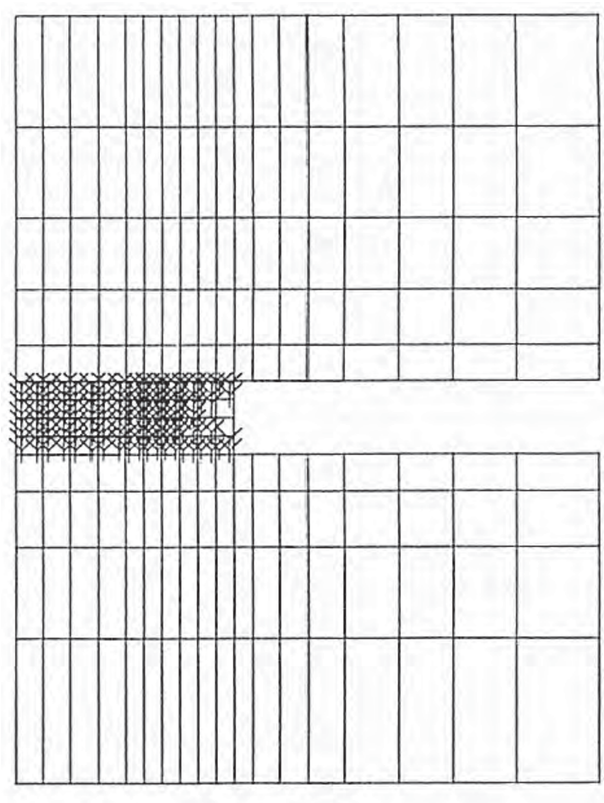
Figure 11. Vertical and horizontal pillar stresses, determined by the elastic-plastic finite-element solution for different models.



Model A



Model B



Model C

Figure 12. Spread of the yield zone in the mine structure for the three models.

7 CONCLUSION

Based on the modelling results presented above, the following conclusions may be drawn:

- The strain-weakening behaviour of rock layers around a mine opening was simulated using an advanced non-linear elastic-plastic finite-element model, which accounts for the residual strength after failure. This simulation was achieved using a step-by-step iterative computational procedure in which the rock material's stiffness was updated after each run according to the initially applied load, until the solution reached the final equilibrium steady state of the mine structure. The numerical results clearly demonstrate the limitations of the linear model when it comes to realistically representing the overall structure behaviour Fig. 5, particularly when the structure of the rock mass is relatively weak, and that a non-linear approach was justified.
- As progressive mining was simulated in the model, the maximum load in the pillar increased and trans-

ferred laterally towards the centre of the pillar as yielding occurred, this trend of lateral stress transfer and load build up in the core of the pillar is consistent with that observed in situ.

- Based on the simulation results, the upper and lower bounds of the overall room and pillar stability were obtained. Parameters such as the roof, the pillar width, w_p , the extraction height, h_p , the variability of the pillar, roof and floor strength have been shown to significantly affect the mechanism of roof, pillar and floor yield.

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MONITORING IN ANALIZA TRESENJA TAL V PREMOGOVNIKU VELENJE

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o avtorjih

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izvleček

Na Premogovnik Velenje so se redno naslavljale pritožbe zaradi povečanega tresenja tal. Postavljen je bil mikroseizmični sistem za spremljanje tresljajev na površini, v bližnjih naseljih, pa tudi na odkopih. Rezultati meritev so bili detajlno analizirani in predstavljeni zainteresirani javnosti skupaj z raznimi standardi in predpisi za varno tresenje tal, ki veljajo v posameznih državah. Tozadevni predpisi in standardi v slovenski regulativi ne obstajajo. Poleg tega je bil postavljen tudi sistem za avtomatsko beleženje podatkov o tresenju tal in objavljanje teh na spletnih straneh. Navedeno je imelo za posledico drastično zmanjšanje števila pritožb. Rutinski mikroseizmični monitoring tresenja tal je tako postal del obratovalnega monitoringa, saj so se pokazala določena pravila pri seizmičnem odzivu okolne hribine na rudarska dela.

ključne besede

stebrni udar, seizmičnost, premogovnik, širokočelno odkopavanje, rušenje krovnine, odziv javnosti

MONITORING AND ANALYSES OF SEISMIC EVENTS AT THE VELENJE COAL MINE

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Abstract

Complaints about ground shaking and tremors were regularly addressed to the management of the Velenje Coal Mine. A micro-seismic monitoring system was set up on the surface in nearby urban areas and also directly in the vicinity of the mining activities. The results of these measurements were carefully analysed and presented to the public together with various safe-vibration-limit standards (in this case national standards). A system for automatically publishing measurements immediately after the event is recorded was also set up. This resulted in a dramatic reduction in the number of complaints. Routine micro-seismic monitoring became part of the regular monitoring of mining activities as some patterns of seismic response to mass mining were revealed.

keywords

rockbursts, seismicity, coal mine, longwall mining, caving, Velenje, Slovenia, public response

1 INTRODUCTION

The Velenje coal basin has a very thick layer of lignite. Modern mining technology on large excavation plates ensures the viability of the operation, despite the low combustion value. The main consumer is the nearby thermo-power plant.

Mine tremors and even rockbursts follow the excavation, although the geological formation is soft. Seismic monitoring systems on the surface and in the mine gave us an invaluable insight into the processes that took place during the excavation.

2 GEOLOGY OF THE COAL DEPOSIT

The lignite seam at the Velenje Coal Mine extends under almost the entire Šaleška Valley, its deposit being 8.3-km long and 2.5-km wide.

The thickness of the coal ranges from 20 to 160 m. The nearest coal is 60 m under the surface, in a seam that is 10 – 35-m thick. The largest amount of coal can be found at a depth of 290 m, where the thickest seam has been confirmed. The coal layer is 100-m thick at a depth of 400 m. The north area of the coal seam inclines at an angle of 10 – 15°, and gradually becomes thinner at a depth from 100 to 300 m, where in the south area it ends abruptly at a depth of 150 m under the surface. The quality of the coal decreases from the hanging wall to the footwall of the seam. The lower calorific value of the coal seam still being exploited is down to 7.5 MJ/kg. The longitudinal section of the coal seam is shown in Figure 1.

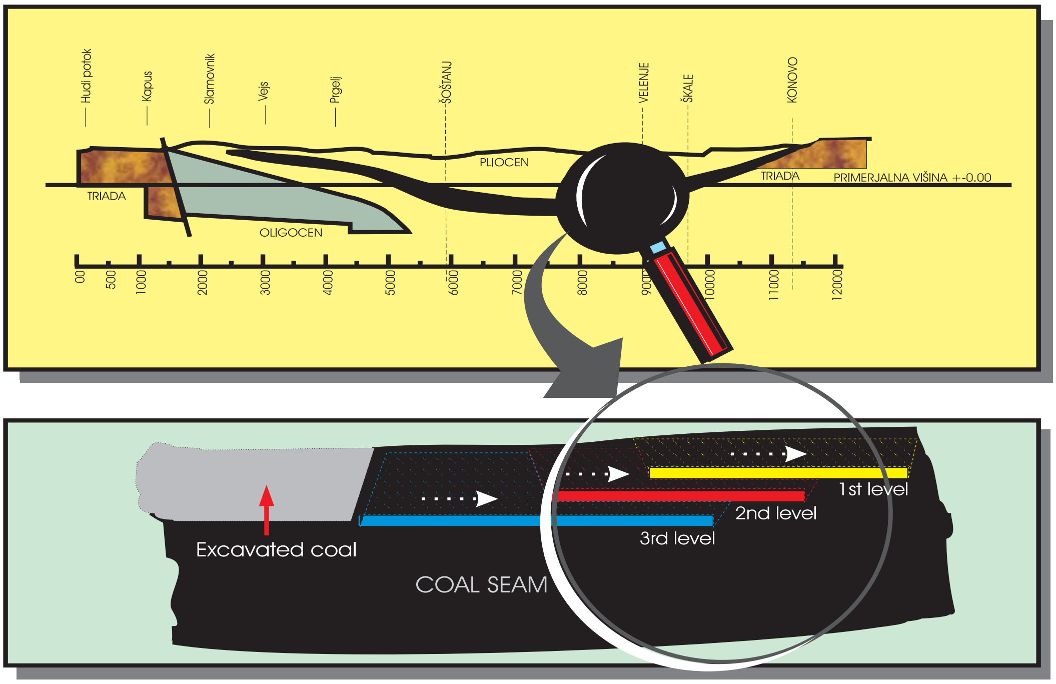

Figure 1. Longitudinal section of the coal seam and the sequence of extraction.

The river and lake alluvia consisting of sand and clay, whose thickness totals no more than 460 m, represent the hanging wall of the seam. Immediately above the coal seam there are clay layers, ranging from a few hundred meters to a minimum of six meters. They prevent water inflow into the haulages.

The footwall of the seam consists of clay and marl lying on triassic limestone and dolomites. In the hydrological sense, the depression is extremely water-bearing, especially in the Pliocene area.

The coal seam in whose hanging wall and footwall most roadways can be found is tectonically little cracked, and the fractures caused by the sinking of the seam are mostly of a local character.

The whole formation is soft with low values of the geomechanical properties. Brittle failure of the coal can be expected, based on experiences with laboratory compressive-strength tests. The geomechanical properties are collected in Table 1.

3 MINING METHOD

The mining method used in the Velenje Coal Mine is known as the Velenje Mining Method and is unique in world mining technology. The basic principle of the work on the faces was based on winning the lower and the upper excavation part of the face at a floor-level height of 10 – 15m.

The cracking of the roof influences considerably any further mining. The first-floor level advances only with the lower excavation part, and crushes the hanging wall and the coal to the extent that efficient excavation from the upper area is made possible with the following floor level.

With the Velenje mining method the length of the longwalls amounts to 80 – 160 m and the length of the panels varies from 600m to 800m. The maximum face inclination in the direction of the advancing totals 15 degrees, and 7 degrees inclined along the face.

The technological coal-mining procedure is divided into:

- winning the lower excavation section of the coalface,
- winning the upper excavation section of the coalface.

The double-drum shearer excavates the coal in the lower section of the longwall face.

The coal in the upper section of the face is excavated by winning the coal through the gate in the shield, or over the canopy of the shield of the section.

The working cycle is completed when all the coal from the upper excavation part is extracted. The coal from

Table 1. Geomechanical properties of the different layers.

	Density (kN/m^3)	Moisture content (%)	Uniaxial compressive strength (Mpa)	Tensile strength (Mpa)	Elasticity modulus (Mpa)	Poisson modulus (/)	Cohesion (Mpa)	Friction Angle φ, (°)
Hanging wall – upper part	20.9	24.4	0.85	0.08	140	0.35	0.4	15.0
Hanging wall – lower part	19.2	32.6	2.50	0.23	430	0.20	0.7	17.0
Coal bed - upper part	12.6	39	8.40	0.92	480	0.25	0.7	30.0
Coal bed - lower part	13.6	35	5.4	0.59	480	0.30	0.7	30.0
High ash coal	17.7	25.6	1.6	0.17	375	0.35	-	-
Footwall	23.6	10.0	4.9	0.44	2917	0.30	1.4	21.6

the upper excavation part is mined systematically after a certain number of cuttings in the lower part. The number of cuttings in the cycle depends on:

- the working height,
- the coal-face length,
- the slope and inclination of the face,
- the number of sectors in the upper excavation section along the face,
- the degree of coal crushing in the upper excavation section of the coalface.

The sequence of working phases is changed with regard to what was stated above. They can also be carried out simultaneously, in event of favourable conditions.

4 TREMORS AND MINING

Tremors regularly accompany longwall mining. They are felt by local inhabitants of the nearby town of Šoštanj and the village of Pesje, which is only a few hundred metres away, measured in a horizontal distance from the longwall faces (Figure 2, next page). Most of the tremors that were felt by local inhabitants were not observed in the mine and also did not cause any damage to the mine infrastructure. But the local community has organized and started a strong media campaign against the mine authorities, which from time to time has been very heated. New, minor superficial cracks were regularly reported to the mine and damage compensation was

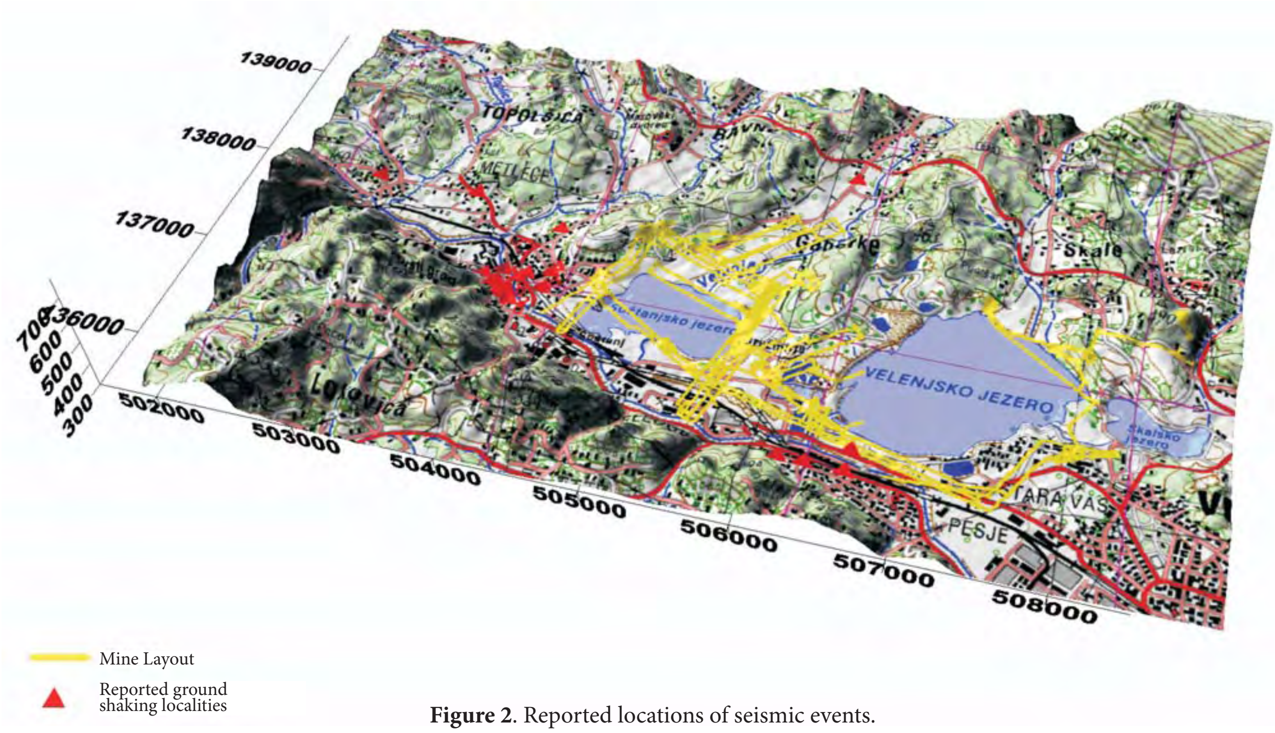

Figure 2. Reported locations of seismic events.

claimed. After careful examination of the reported damage it was found that the cracks could not be ascribed to tremors, rather they were ascribed to other causes, like uneven settlements of foundations, changes in humidity and constructional reasons.

It was very difficult to explain to the local inhabitants that these cracks were not caused by the mining. The approach to the problem was very systematic. First, we started to record the public's response on a toll-free telephone line, where every caller was asked to report the location of an event felt and a description of the event. Then all the locations were summarized and plotted on a map with a link to the layout of the mine. In the centre of the areas with the greatest density of complaints – in the areas of Šoštanj and Pesje – ground-vibration monitors were installed. The system is trigger based, with the trigger set to 0.1mm/s, which is about 5 times less than human sensitivity to ground vibrations. This ensures that we do not miss an event that can be felt by the local inhabitants.

5 RESULTS OF THE MICRO-SEISMIC MONITORING

The results of the measurements soon revealed that on the most seismically active days, three to five seismic events were recorded, with maximum peak particle velocities of 2 – 3 mm/s at frequencies of 7 – 10 Hz. The typically recorded values were from 0.7 to 1.1 mm/s at the same frequencies. This means most of the tremors were weak, and so could not cause any damage to the buildings.

When the results were presented to the public there was a lot of scepticism and disbelief among the local inhabitants. Measurements were collected for a period of more than one year and sent to independent and internationally acknowledged experts on blasting techniques and vibration. The experts' opinion was that the damage due to vibration in terms of a reduction in utility values is unlikely to have occurred. The vibrations at the recorded levels were not able to damage buildings in a causal manner according to the DIN 4150 standard. However, already existing damage could change, and if damage was found, it must be assumed that other causes are responsible for this damage.

We openly presented the conclusions from the experts and presented the measurements to the public. In the meantime we also set up a system for automatic measurements and published the results on the company's web pages, which is the most convincing proof that we are ready to assist local inhabitants with information. In the first months we received lots of calls immediately after a tremor from people asking where the results of measurements could be seen. So instead of complaint calls we are now receiving calls from people who are interested in things like "What are safe vibration limits?", "What are mm/s?", "What other things can cause cracks in my house?" To answer these and other questions we have supplemented the web pages with answers to these frequently asked questions. These measures resulted in a drastic reduction in the number of complaints.

6 CHARACTERISATION OF EVENTS

The seismic monitoring system on the surface and in the mine gave us an invaluable insight into the processes that took place. Figure 3 displays the seismic activity for December 2004 in terms of days and the hour in the day. Stronger events occur at the beginning of the week and are connected with the cracking of the console in the hanging wall that is built for the weekend. With the constant and progressive progress of the longwall the level of activity decreases and the number of events increases. The accumulated energy is released in smaller amounts. We can see the decrease in the activity in the time of shifts in Figure 3b (6, 14 and 22 hours). The relative amplitude shown in Figure 3 was used to calculate the energy of seismic events by considering the distance and depth difference from the seismic event to the seismic station.

Caving is the most critical process during coal extraction. There have been previous studies of the caving processes associated with the longwall mining, for example Hatherly et al, (1997). An accurate location of the mine tremors is possible only with the use of an in-mine seismic system. We have also deployed a mine-wide seismic system consisting of accelerometers and signal transmission to the surface. An example of an accelerogram is displayed in Figure 4.

The values are measured in volts and a factor of sensitivity 1/G=9,684 m/(Vs^2) should be used to convert the values to ground-vibration accelerations. The locations of the events are usually above the level of the excavation. The process of caving is taking place in that area. High stresses fracture the coal. The process can be improved by de-stress blasting or preconditioning (Toper et al., 1997).

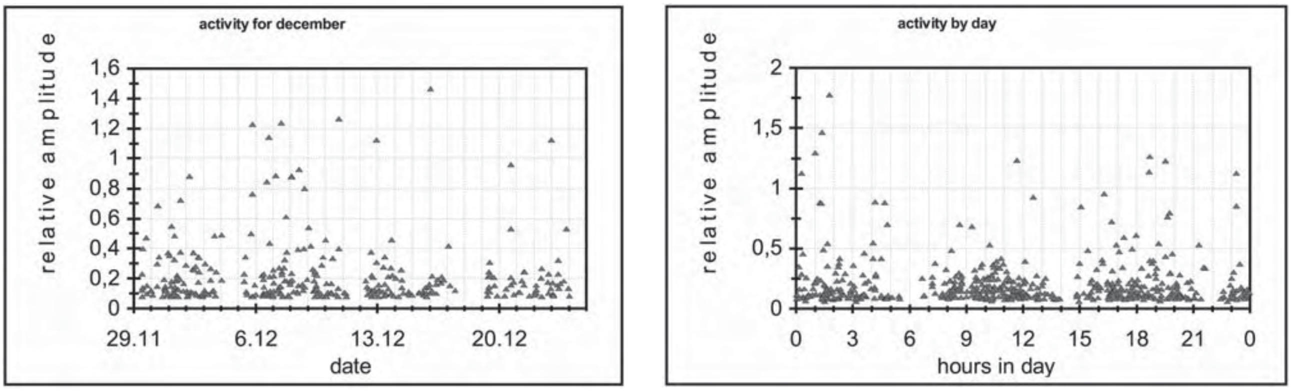

Figure 3. Activity for December 2004 (a) and its display in terms of hours in the day (b).

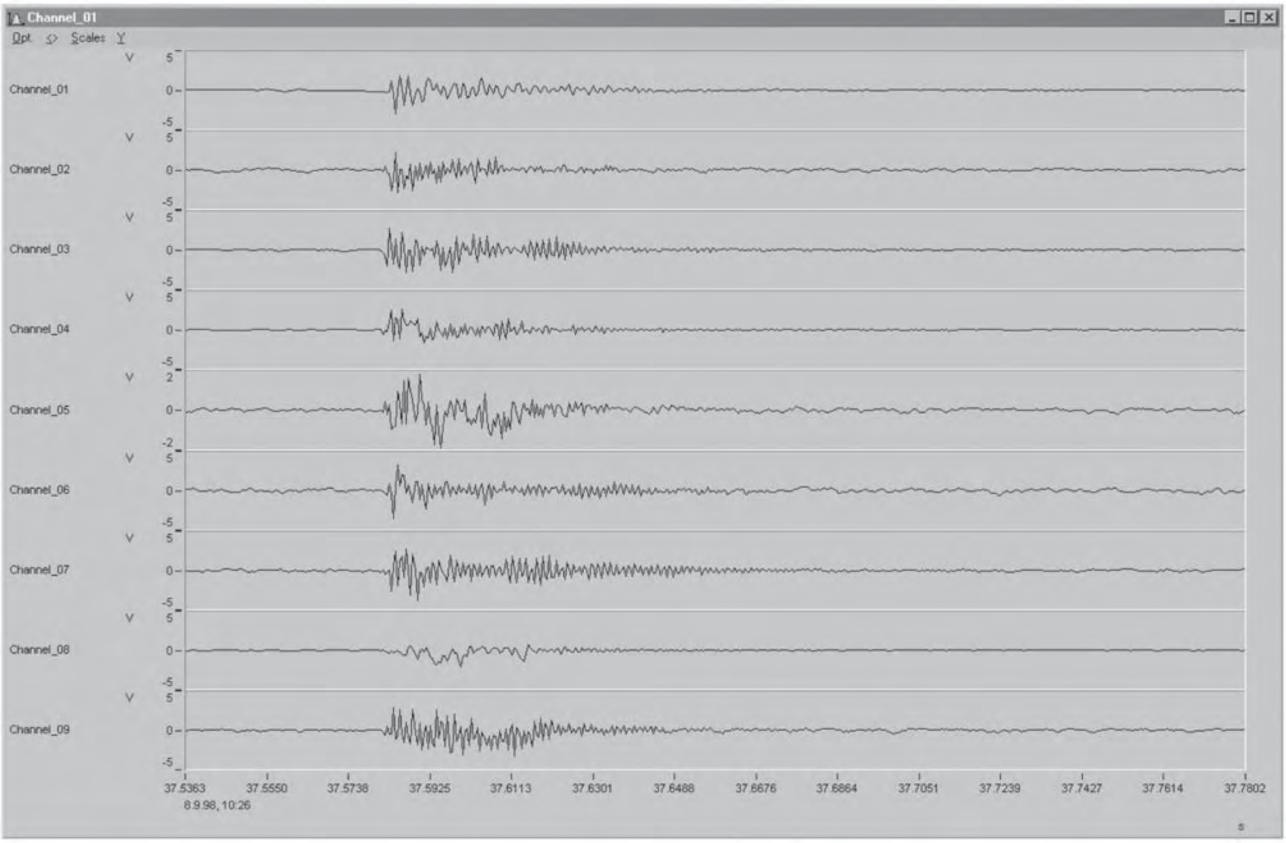

Figure 4. An example of the accelerogram recorded by the in-mine system. time is in seconds, amplitude is in volts.

7 ANALYSIS OF THE FOCAL MECHANISM

Even if the shaking tremors were now better described, some uncertainty still remains. Especially the question of whether all the big events originate from the mine works or whether their origin is natural. For these reasons the analysis was widened and also the national seismological station was used for analyzing the tremors (Figure 5). The answer is that some stronger tremors were registered by the Slovenian seismological stations and some were not. Another reason is that only for the national seismological stations are the sensors' orientation data provided accurately enough for a first-motion analysis. For these reasons, the selection of events registered at the mine and the Slovenian seismological observations network was needed. In fact there were just a few events that we were able to prove had their origin in the area of the mining works. For a better understanding of the governing mechanism we decided on an analysis of the fault-plane solution. The fault-plane solution (or the focal-mechanism solution) is a method for identifying the type of earthquake (Cox and Hart, 1986). The fault-plane solution is constructed from the detected signals of different stations and gives an insight into the type or the source of the earthquake (normal fault, thrust fault or strike slip). To achieve a fault-plane solution, it is necessary to know the azimuth as well as the angle of incidence and the type of the first wave (compression or dilatation) that reaches the detecting station. The data is projected onto a circle in such a way that the azimuth is taken as an angle and the angle of incidence is taken as the length of a line. At the end of the line a mark is placed, depending on the type of wave.

Our aim was to identify whether the events observed in the mine and in the national observation nets mainly have their origin in normal fault movements or the components of thrust fault movements. If they were to have their origin in thrust fault movements their origin would be unlikely to be due to the mining works. The events were first compared on the basis of their frequency and the calculated seismic moments. Seismic moment is a quantity used to measure the size of an earthquake (Aki, 1966). The seismic moment of an earthquake is typically estimated using whatever information is available to constrain its factors. For earthquakes the moment is usually estimated from ground-motion recordings of earthquakes (Westway, 1992). In 1970 Brune set up this relation for a dislocation along the fault:

$$u = (\sigma / G)\beta * t" \qquad (1)$$

where:

- σ - is the effective stress (difference in the effective stress on a fault before and after dislocation)
- G - is the shear modulus
- β - is the velocity of the shear waves
- R - is the distance between the hypocenter and the seismological station
- r - is the fault plane distance
- $t"$ - $t\text{-}R/\beta$
- f - $(S/0.8)^{1/2}$, where S is a conversion factor for shear waves in compression waves

Figure 5. Seismological stations used for the analysis of focal mechanisms. The yellow stations had a sufficient number of good signals for making the analysis.

Using a Fourier transformation of Equation (1) means that Equation (2) can be found (Stanković, 1988):

$$u(\omega) = R_{\Theta\phi} f(r/R)(\sigma\beta/G)(\omega^2 + \alpha^2)^{-1/2} \qquad (2)$$

Equation (2) describes the amplitude spectra of the dislocation on the free distance from the fault plane. In Equation (2) the factor ($R_{\Theta,\phi}$) defines the seismic waves that we are observing. The α and f are very well-known factors, usually f=1 when S=0.8 and α=2.21 β/r. If we are calculating the spectra of the dislocation movement along the fault using Equation (2) and putting the calculated values on the y axis composed of log (ω) and the ordinate of log ($u(\omega)$) we obtain the diagram in Figure 6.

Looking at Equation (2) and taking into consideration the well-known expressions for the seismic moment $M_o=(18/7)\sigma r^3$ and $\sigma^2=(14\pi/9)\,(\beta/r)^2$ (Brune, 1970) and setting ω to 0 we obtain the following equation:

$$u(\omega) = R_{\Theta\phi} M_o \eta (4\pi\rho\beta^3)^{-1} \qquad (3)$$

From Equation (3) we can see that the seismic moment depends on the spectrum of the dislocation at low frequencies. This implies that using the low spectrum frequencies we are able to compare the events registered

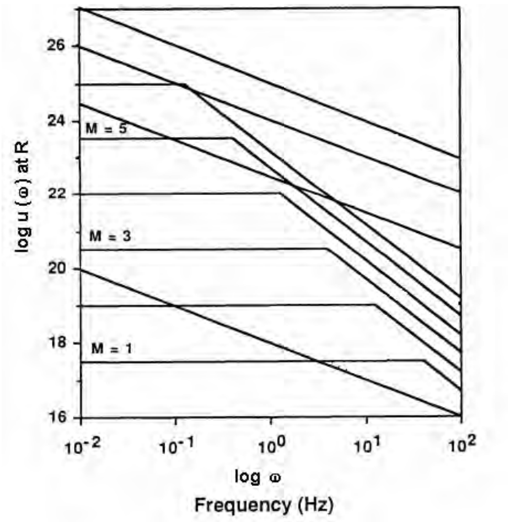

Figure 6. Displacement spectra (Brune, 1970).

on the mining seismological nets with those on the Slovenian seismological net.

On the basis of the theory described above, only a few events could be identified on both observation networks. The uncertainty was even greater if we looked at the first arrivals on the seismological stations. So, in the end, only four events had data good enough for a first-motions analysis (Figure 7).

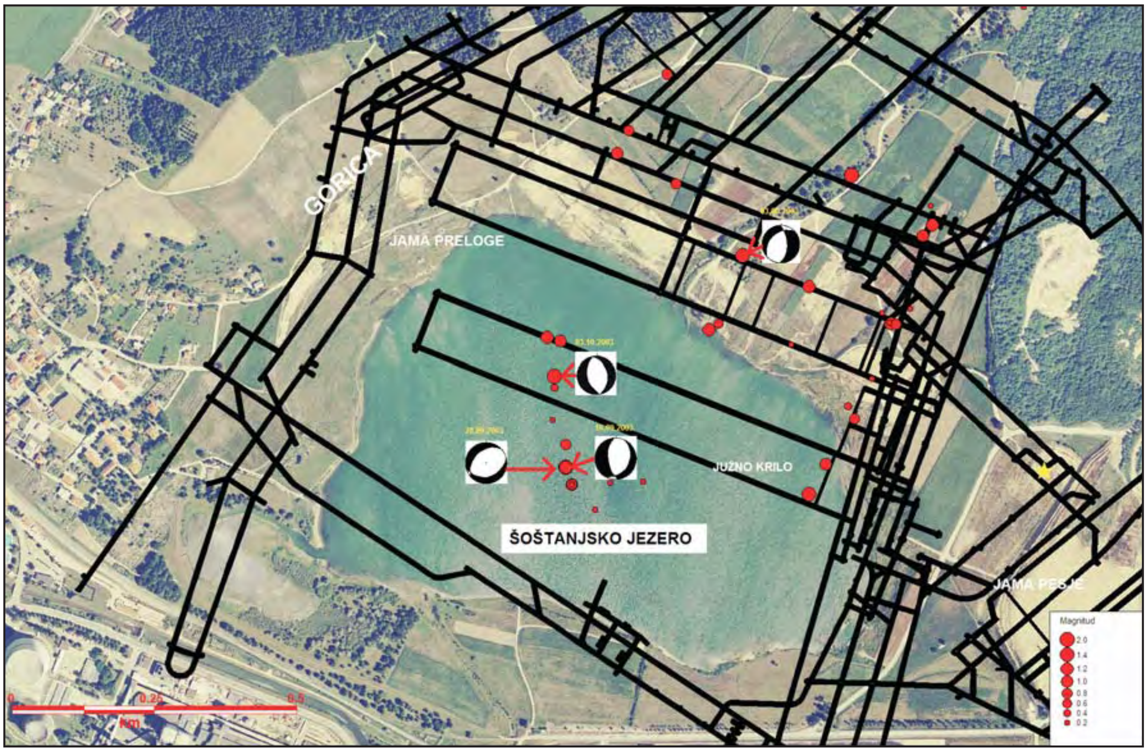

Figure 7. The results of the focal-mechanism solution analysis.

It seems that with the four analyzed events the normal movements are present in the governing mechanisms of the tremors. This can be associated with the dilatations occurring due to the excavations of the coal seam. Because of the data uncertainty we cannot definitely associate all the major events with the mining works, but on the basis of the first analysis, as some indications are strong enough, further work in this direction will be carried out.

8 CONCLUSIONS

A mine-wide seismic monitoring system has become an essential part of mining-surveillance monitoring systems, especially for mines operating near urban areas. It provides data about the time and the intensity of recorded seismic events at the locations where most of the complaints are coming from.

The surface station in the nearest village, Pesje, and the town of Šoštanj convinced us that the mine tremors do not cause damage to the buildings, as they are much smaller than the allowed values, according to the DIN 4150 standard. The opinion of independent experts confirmed this statement on the basis of measurements for a period of more than one year. A first-motions analysis was also made, with the aim of better understanding the governing mechanism of the tremors. It seems that some major events also had their origin in the mining works rather than in natural geological events.

We openly presented the conclusions and made the results of the online measurements available to the public. So instead of complaint calls we are now receiving calls from people who are interested in things like "What are the safe vibration limits?", "What are mm/s?", "What else can cause cracks in my house?" These measures resulted in a drastic reduction in the number of complaints.

Seismic monitoring helped us to obtain information about the processes in the mine and to get the response of the coal formation to the mass mining. The response is immediate and, therefore, it is controllable. We also found that some parts of the longwall face responded to mining with a lower intensity of seismic events than others. This phenomenon is especially noticeable at the start of the longwall excavation.

With time the database of measurements is increasing, as is the knowledge base in that area. So it is very important to maintain uninterrupted seismic monitoring of mining operations in the future.

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ANALIZA KONCENTRACIJE IN USEDANJA SUSPENDIRANEGA MATERIALA V AKUMULACIJSKIH JEZERIH

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izvleček

Prispevek obravnava problem sedimentacije lebdečih plavin v akumulacijskih jezerih. Kot primer je prikazano jezero hidroelektrarne Boštanj na reki Savi.
Cilj opisanih raziskav je bil ugotoviti vrsto in količino sedimentiranega materiala v jezeru v izbranem časovnem obdobju. V ta namen je bila preiskana mineralna in kemična sestava ter koncentracija in velikost suspendiranih delcev pri vtoku vode v akumulacijsko jezero in ob njenem iztoku.
Za ugotovitev vsebnosti lebdečih plavin je bilo odvzetih 24 vzorcev vode z območja vtoka in iztoka vode iz akumulacijskega jezera. Istočasno je bil izmerjen pretok reke Save. Trdni delci so bili iz vode izločeni s pomočjo usedanja in v zaključni fazi izparevanja vode. Rezultati preiskav so pokazali, da se koncentracija suspendiranega materiala na posamezni lokaciji spreminja v odvisnosti od pretoka vode in jo je mogoče izraziti z eksponentno funkcijo.
V sestavi lebdečih plavin se pojavljajo karbonati, muskovit/illit, kremen in klorit ter v manjši meri plagioklazi in organski detritus. Glede na velikost zrn se preiskani materiali uvrščajo med melje.
Ugotovljeno je bilo, da je količina suspendiranega materiala pri enakem pretoku vode ob vtoku v akumulacijsko jezero večja kot ob iztoku. Razlika predstavlja material, ki se je v jezeru sedimentiral zaradi zmanjšane hitrosti vode kot posledice zajezitve reke. Rezultati preiskav zrnatosti so pokazali, da so se usedali predvsem delci velikosti 20 μm do 100 μm. Primerjava mineralne sestave vzorcev z obeh odjemnih mest je pokazala nekoliko manjši delež karbonatnih zrn in težkih mineralov ter večjo vsebnosti organskega detritusa in glinenih delcev na mestu iztoka vode iz jezera.
Ob upoštevanju dejanskega pretoka vode v obdobju od julija 2006 do julija 2007 ter preiskanega razmerja med pretokom vode in količino suspendiranega in sedimentiranega materiala, je ocenjena skupna količina sedimentiranega materiala v tem času.

ključne besede

lebdeče plavine, sedimentacija, transport sedimentov, dolinska pregrada

ANALYSIS OF CONCENTRATION AND SEDIMENTATION OF SUSPENDED LOAD IN THE RESERVOIRS

BOJANA DOLINAR, HELENA VRECL-KOJC and LUDVIK TRAUNER

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Abstract

This paper deals with the sedimentation of suspended load in the reservoirs. As an example the reservoir of the hydroelectric power plant Boštanj on the Sava River is shown. The objective of the described studies was to determine the quantity and type of deposited material in the reservoir during the selected time period. For this purpose, the mineral and chemical composition, and the concentration and the particle size of the suspended load at the intake of the water into the reservoir and at its outflow were examined.
In order to determine the concentration of the suspended load, 24 water samples from the area of the intake and outflow from the reservoir were taken. At the same time the discharge of the Sava River was measured. Solid particles were removed from the water with the help of sedimentation and in the final stage of water evaporation. The results of the studies showed that the concentration of the suspended material was changing in relation to the location and the flow rate of the water. This ratio can be described with an exponential function.
In suspended load composition carbonates, muscovite/illite and quartz dominate; however, chlorite was also found, as well as small quantities of plagioclase and organic detritus. With regard to the size of the particles the examined samples are classified as silt.
It was determined that the concentration of the suspended load, at the same flow rate of water, at the intake into the reservoir is larger than at the outflow. The difference is represented by the material that was sedimented in the reservoir due to the decreased speed of the water as a result of the river's impoundment. A comparison of the composition of the samples from both collection sites showed that at the outflow site of the water from the reservoir there is a somewhat smaller share of carbonate grains and heavy minerals than at the intake site, and a higher content of organic detritus and clay particles can also be observed. Considering the actual discharge of water in the period between July 2006 and July 2007 and the examined ratio between the flow rate of the water and the quantity of suspended and deposited material, the total quantity of sedimented material in this period was estimated.

keywords

suspended load, sedimentation, sediment transport, water storage reservoir

1 INTRODUCTION

Because of the washing away of weathering material, the erosion of banks or, as a result of artificial interventions, various inorganic and organic materials can be found in watercourses. Due to the water turbulence, the load is transported in a suspended form or by rolling along the river bottom. In a water environment the load is floating under the condition that its sedimentation speed is lower than the vertical speed component of the turbulence regime; otherwise, it quickly starts to sink. The speed of the sinking load also depends on other characteristics, such as the water temperature and the concentration of suspended matter, which consequently affect the density and the viscosity of the fluid.

The paper discusses survey of the suspended load in the water-storage reservoir of the hydroelectric power plant

Boštanj on the Sava River. The concentration and the particle size of the suspended load and its mineral and chemical composition were examined. On the basis of these data, the total quantity and the type of sedimented material in the reservoir in the selected time period were assessed.

2 SAMPLING AND TESTING METHODS

The water samples, from which the suspended material was removed, were taken at the intake of the water into the reservoir of the HPP Boštanj and at its outflow (Fig.1). For reasons of data comparability, the water was always taken at the same site and depth (1 m). A total of 24 samples were collected, and each contained at least 40 l of water. At the site of the sample collection the discharge of the Sava River and its temperature were examined during the sampling (Table 1).

The concentration of suspended load in the water was examined at the Soil Mechanics Laboratory at the Faculty of Civil Engineering in Maribor. The solid was removed from the water with the help of the sedimentation of particles and water evaporation (Table 1).

The particle size analyses of the solids were determined by the Geological Survey of Slovenia using a laser particle sizer "analysette 22"/ Nano Tec made by FRITSCH GmbH - Manufacturers of Laboratory Instruments, Germany. Analytical instruments based on laser diffraction for the determination of a particle size distribution use the physical principle of the scattering of electromagnetic waves. The design consists of a laser beam directed through a measuring cell to a detector. A dispersion module transports the particles to the measuring cell and through the laser beam. The light scattered in proportion to the particle size is projected by a lens onto a detector. The particle size distribution can be calculated from the distribution of scattered light with the help of complex mathematics. A total of 16 samples were examined.

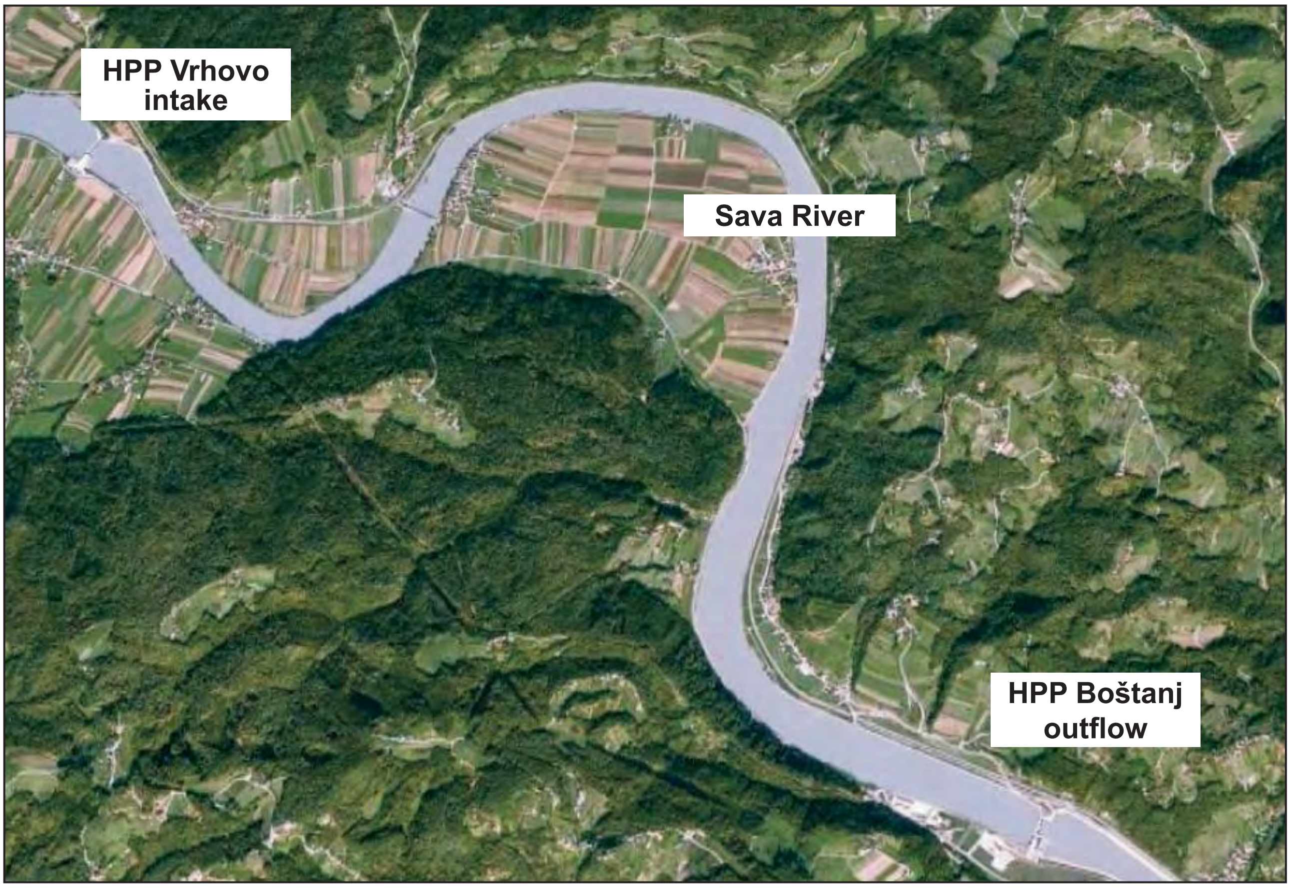

Figure 1. Reservoir of the HPP Boštanj.

Table 1. Time of sampling, temperature of water (T), discharge (Q), concentration of suspended load (c).

Sample	Date	hour / min.	T (°C)	Q (m^3/s)	c (g/m^3)
1 Intake	01.09. 2006	12 / 20	13,3	175	6,8
1 Outflow		13 / 00	16,6	152	1,1
2 Intake	20.09. 2006	8 / 40	13,0	252	12,7
2 Outflow		8 / 40	13,0	252	8,6
3 Intake	26.10. 2006	8 / 40	12,0	248	19,6
3 Outflow		8 / 20	12,5	264	10,0
4 Intake	15.11. 2006	11 / 50	9,5	65	1,7
4 Outflow		12 / 30	9,5	61	0,8
5 Intake	23. 11. 2006	12 / 00	10,0	210	18,3
5 Outflow		12 / 30	10,0	180	18,3
6 Intake	24.11. 2006	12 / 30	10,0	134	5,8
6 Outflow		12 / 50	10,0	130	8,3
7 Intake	11.12. 2006	11 / 20	9,5	407	47,5
7 Outflow		11 / 45	9,5	383	25,0
8 Intake	24.01. 2007	11 / 05	7,0	478	75,4
8 Outflow		10 / 40	9,0	525	40,8
9 Intake	09.03. 2007	11 / 55	10,0	340	15,8
9 Outflow		12 / 20	10,0	316	11,3
10 Intake	24.04. 2007	10 / 05	15,0	100	6,6
10 Outflow		10 / 30	15,0	114	0,8
11 Intake	21.05. 2007	7 / 50	17,0	74	1,7
11 Outflow		8 / 15	17,0	63	5,8
12 Intake	05.06. 2007	9 / 40	19,5	79	5,2
12 Outflow		9 / 08	19,5	62	3,7

The bulk mineralogy of the composed samples from each site was determined by the Geological Survey of Slovenia using X-ray diffraction techniques. Samples were scanned using a Philips PW 3710 X-ray diffractometer with an 1820 goniometer, an automatic divergence slit, and a curved-crystal graphite monochromator. The instrument was operated at 40 kV and 30 mA using Cu-Kα radiation.

The microscopic analysis of the solids was determined by the Geological Survey of Slovenia. Because of a relatively high content of clay fraction and other submicroscopic particles, this fraction was removed by leaching before the examination of the samples.

The results of the chemical analyses of the composed samples from both sites were used to check and confirm the quantities of the individual minerals in the solid. The chemical composition was determined by Acma Analytical Laboratories Ltd., Vancouver, Canada. The inductively-coupled plasma emission spectrometry method was used to determine the main elements quantitatively and qualitatively, whilst inductively-coupled plasma mass spectrometry was used to determine the trace elements. Carbon and sulphur were determined using a Leco CS444 element analyser.

3 RESULTS

3.1 PARTICLE SIZE ANALYSIS OF THE SUSPENDED LOAD

Grain size analyses were performed on 16 samples from the intake and outflow area of the water from the reservoir. The samples from both sites were collected simultaneously, and therefore the discharge of the water was similar. In this way it is possible to compare the particle sizes in suspension with regard to the collection site. The results of the analyses show that the suspended load mostly has the size of silt, and only 5-20 % of the grains belong to the clay fraction. Larger grains were found at the water-intake site, when an increased share of the clay fraction was observed at the outflow. The results of the grain size analyses for individual samples are presented in Figures 2 and 3 with the discharges at the times of the sample collection marked in the legend. The difference in the size of the suspended load between the first and the final part of the reservoir is presented even more clearly in Figure 4, where the grain size distribution is provided for the composed samples from individual sites. The ratio between the concentration of the suspended material (g/m^3) and the grain size at the water intake and outflow sites from the reservoir is presented in Figure 5. It is evident that the quantity of larger grains (10-100 μm) of solids in the water is smaller at the outflow from the reservoir than at the intake.

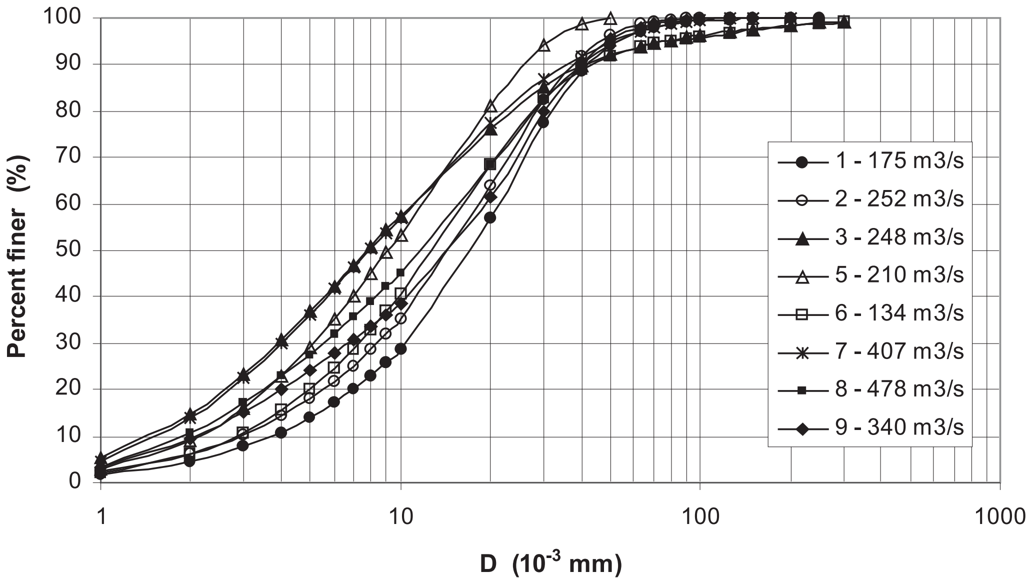

Figure 2. Grain size distribution of suspended load at the water intake into the reservoir of the HPP Boštanj. The legend contains discharges for the time periods of sample collection.

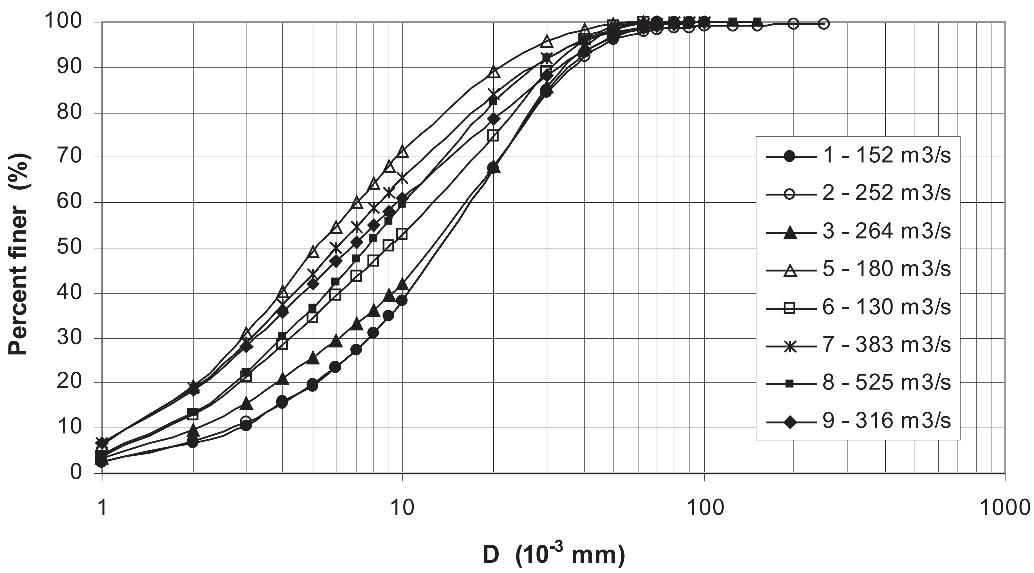

Figure 3. Grain size distribution of suspended load at the outflow of the water from the reservoir of the HPP Boštanj. The legend contains discharges for the time periods of sample collection.

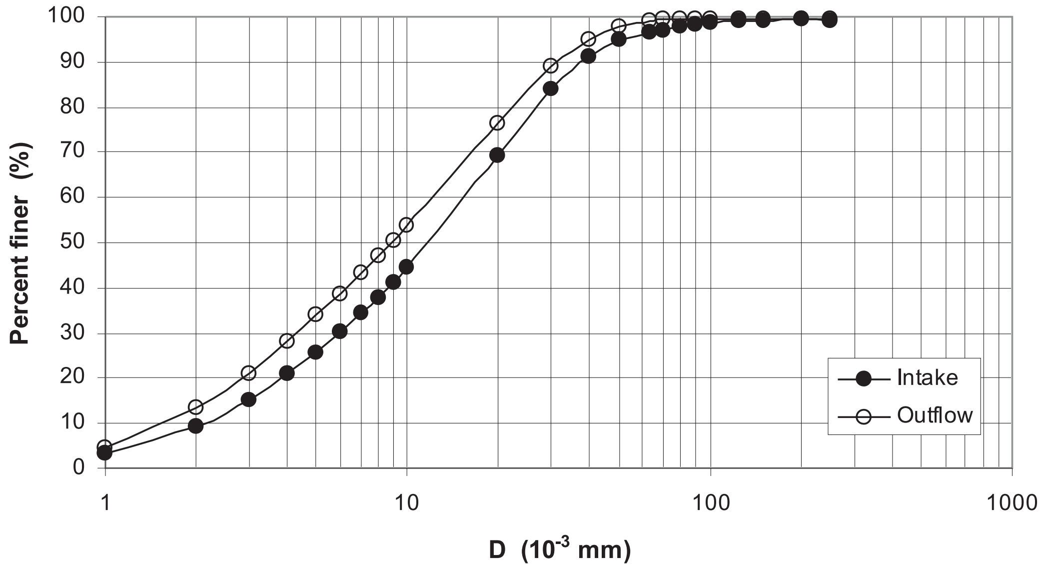

Figure 4. Comparison of the grain sizes of the composed samples of solids from the intake and the outflow area of the water from the reservoir.

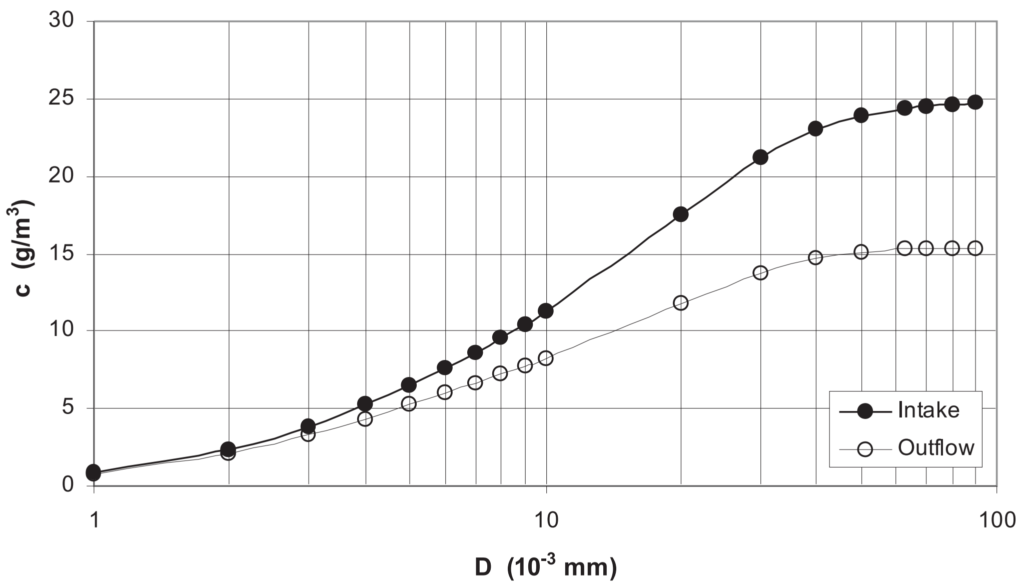

Figure 5. Relationship between concentrations of the suspended load and the grain sizes of the composed samples from both collection sites.

3.2 MINERAL AND CHEMICAL COMPOSITION OF THE SUSPENDED LOAD

The chemical composition of the composed sample of the suspended material from the reservoir and the mineral composition of the composed samples from the water intake and outflow area are presented in Table 2. The comparison of the mineral composition of the samples from both sites shows a smaller share of carbonate particles and larger share of quartz at the outflow of water from the lake than at the intake.

Microscopic examination of the solid from the intake and the outflow of water from the reservoir (Figs. 6 and 7) did not show any special difference in the mineral composition. Only a larger quantity of organic detritus and clay particles and the absence of rare heavy minerals are evident among the suspended material at the outflow of water.

Table 2. Mineral and chemical compositions of the suspended load.

Mineral composition (%)			Chemical composition (%)	
	Intake	Outflow	SiO_2 = 37,76	TiO_2 = 0,54
Muscovite/illite	33	33	Al_2O_3 = 13,43	P_2O_5 = 0,32
Chlorite	15	15	Fe_2O_3 = 5,12	MnO = 0,12
Quartz	17	21	MgO = 2,85	Cr_2O_3 = 0,016
Plagioclase	5	5	CaO = 11,15	TOT/C = 7,62
Calcite	20	18	Na_2O = 0,57	TOT/S = 0,06
Dolomite	10	8	K_2O = 2,20	LOI = 25,6

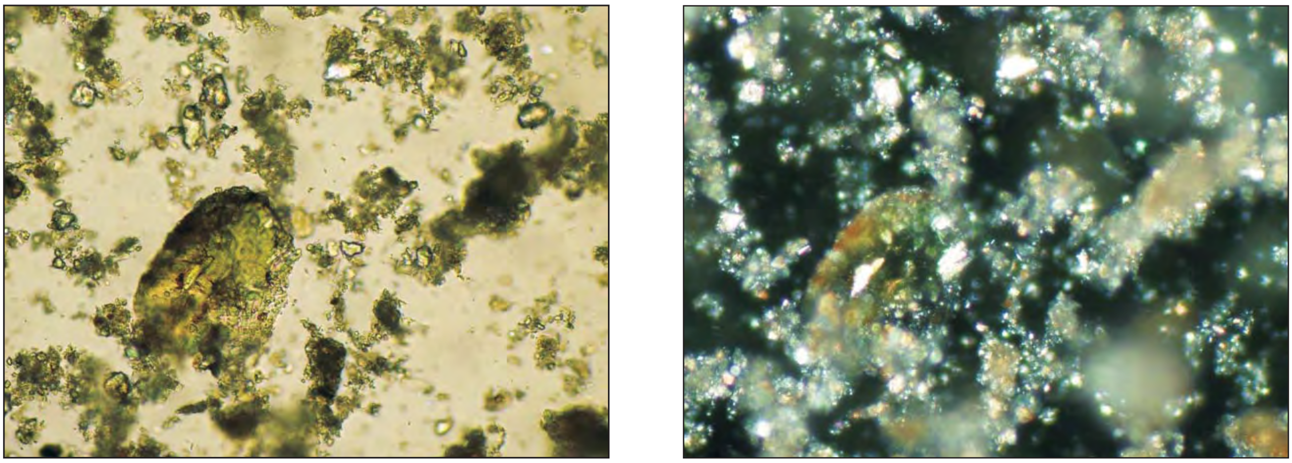

Figure 6. Suspended load at the intake of water into the reservoir of the HPP Boštanj. Green chlorite, transparent carbonate grains, black non-transparent matter and submicroscopic particles of clay and carbonate minerals; II N (Fig. left) and + N (Fig. right), zoom: 190 X.

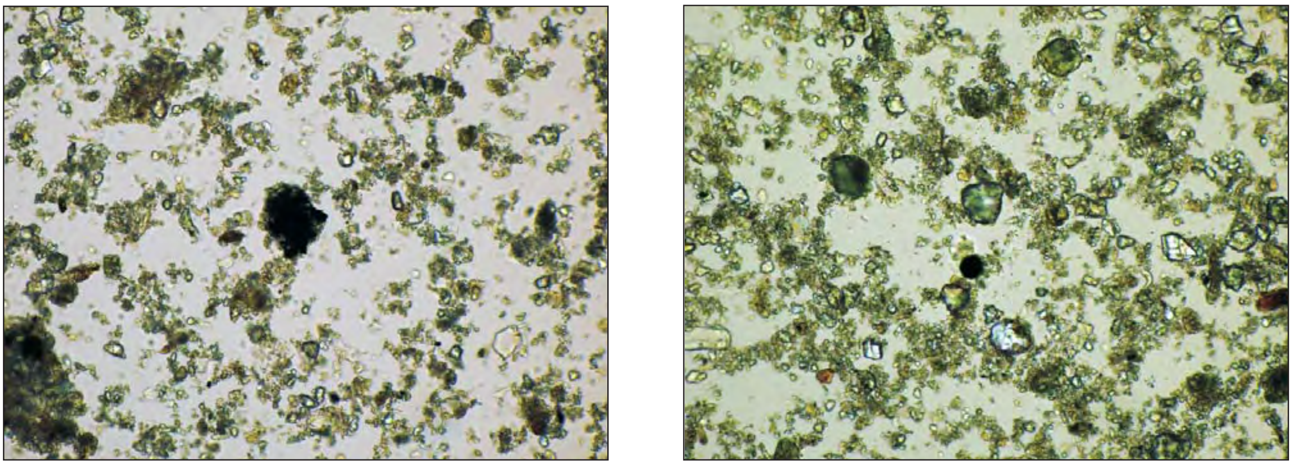

Figure 7. Suspended load at the outflow of water from the reservoir of the HPP Boštanj. Larger grains belong to the black non-transparent matter, transparent carbonate grains, rare sericite leaves, quartz, fine green chlorite and submicroscopic particles of clay minerals; II N (Fig. left) and + N (Fig. right), zoom: 170 X.

3.3 CONCENTRATION OF THE SUSPENDED LOAD

The concentration of the suspended load in the watercourses depends on many factors from the environment, which is why a study of the dynamics of their transport and sedimentation is quite demanding (Rusjan and Mikoš, 2007). However, at an individual measuring station we can see a correlation between the concentrations of the suspended material and the flow rates of the water (Ulaga, 2005; Morris and Fan, 1997).

The results of the measurements at selected sites of reservoir of the HPP Boštanj showed that the share of suspended load is increasing with the increase of the discharge (Table 1). This ratio is shown in Figure 8, in which both variables are presented separately for the samples from the intake and the outflow site of the water from the reservoir. Due to an almost simultaneous collection of the samples from both sites, the discharge was very similar; however, there is a difference in the quantity of the suspended material, which is much smaller at the water outflow.

A comparison of the concentrations of suspended load from both collection sites showed that this ratio is approximately linear (Fig. 9). We can describe it with Eq. (1).

$$c_{outflow} = 0{,}55\ c_{intake} \qquad (1)$$

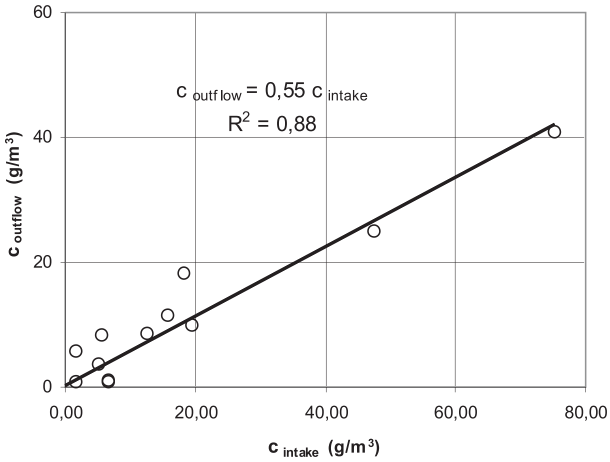

Figure 9. Ratio between the concentrations of suspended load at the intake and at the outflow of water from the reservoir.

From the presentation of the concentrations of suspended load at the water intake and outflow, and discharges (Fig. 10, next page) it is evident that it is possible to describe this ratios with Eqs. (2) and (3).

$$c_{intake} = 1{,}85\ e^{0{,}007Q} \quad (g/m^3) \qquad (2)$$

$$c_{outflow} = 1{,}45\ e^{0{,}007Q} \quad (g/m^3) \qquad (3)$$

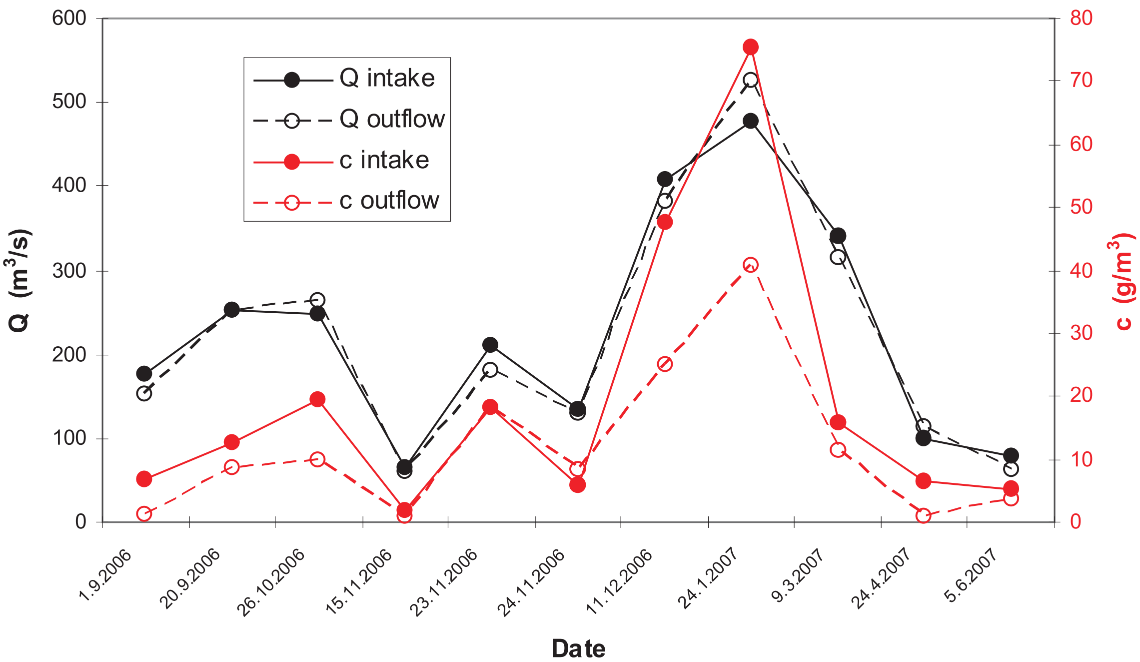

Figure 8. The concentration of suspended load in relation to the discharge and the time periods of sample collection.

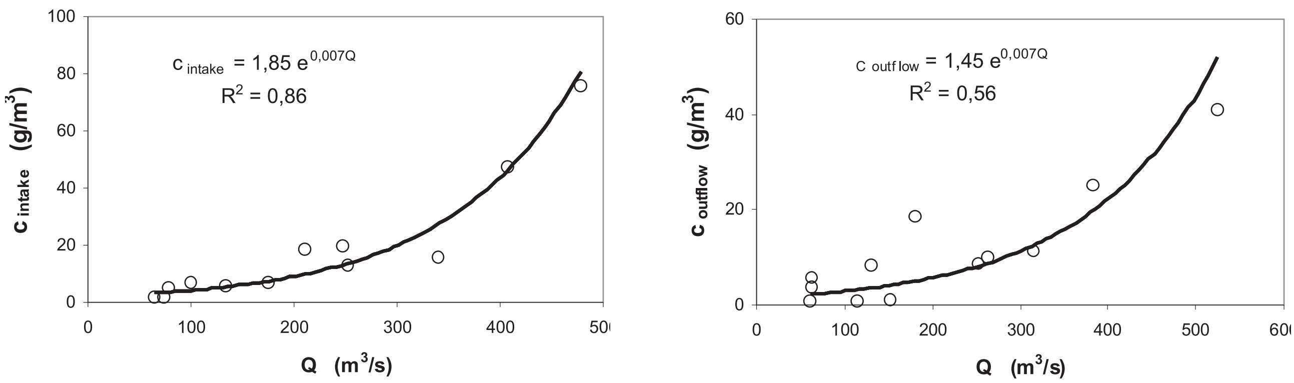

Figure 10. The concentration of suspended load in relation to the discharge at the intake (Fig. left) and outflow (Fig. right) of water from the reservoir of the HPP Boštanj.

3.4 ESTIMATION OF THE QUANTITY OF DEPOSITED MATERIAL

The studies of the concentrations of suspended load at both collection sites showed that there is less suspended load at the outflow of the water from the reservoir than at the intake. The difference is represented by the share of grains that sedimented on the bottom of the reservoir. The quantity of these sediments (c_{sed}) when considering Eqs. (2) and (3) can be expressed in relation to the discharge of water with Eq. 4.

$$c_{sed} = c_{intake} - c_{outflow} = 1{,}85\, e^{0{,}007Q} - 1{,}45\, e^{0{,}007Q} = 0{,}4\, e^{0{,}007Q}\ (g/m^3) \quad (4)$$

An estimation of the quantity of deposited material in the reservoir was prepared on the basis of the actual hourly discharges for the period between 12 July 2006 and 12 July 2007 (Fig. 11). Considering the volume of water flowing through and the portion of deposited material in dependence on the actual discharges (Eq. 4), the estimated quantity of deposited material in reservoir is 1,08 x 10^4 t for selected period of time.

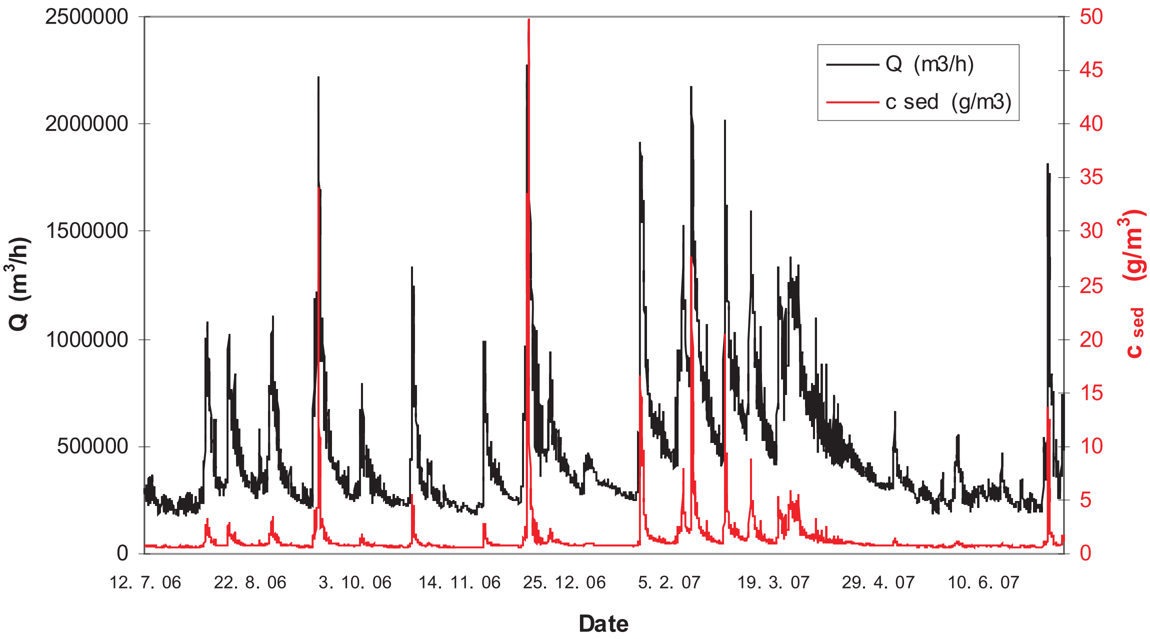

Figure 11. The discharge and the quantity of deposited material for the period between 12 July 2006 and 12 July 2007.

4 CONCLUSIONS

This paper deals with the sedimentation of suspended material in the reservoir of the hydroelectric power plant Boštanj on the Sava River. The objective of the described research was to determine the quantity and type of sedimented material in the reservoir during the selected time period. For this purpose, the mineral and chemical composition, and the concentration and the particle size of the suspended load at the intake of the water into the reservoir and at its outflow were examined. On the basis of the gathered data, the following conclusions can be established:

Because of the changed geometry of the riverbed and, consequently, the lower speed of the water, part of the suspended load is sedimented on the bottom of the reservoir. Based on a comparison of the average quantities of solids in the water at the intake and the outflow, it is evident that at the same flow rate of water this ratio is approximately linear (Eq.1).

The concentration of suspended load increases with an increase in the water discharge; however, this increase is not linear. This dependence can be expressed for the samples of both collection sites with exponential functions (2) and (3).

The quantity of sedimented particles depends mostly on the discharge of water. This ratio in the examined case can be described with equation (4).

The estimated quantity of sedimented material in the period between 12 July 2006 and 12 July 2007 amounts to $1{,}08 \times 10^4$ t. The actual quantity of this material in the resevoir was lower due to its transport at very high discharges of water.

Based on the ratio between the concentration of the suspended load and the size of the grains at the intake and the outflow of the water, it can be concluded that especially the particles with the size between 10 μm and 100 μm are sinking.

The mineral composition of the suspended load is a reflection of the environment in which the Sava River and its tributaries flow. As expected, carbonates, muscovite/illite and quartz predominate, chlorite can also be found, as can plagioclase and organic detritus, in smaller quantities. The structure of the solids at both collection sites is similar. A somewhat smaller share of carbonate grains and heavy minerals and an increase in the content of organic detritus and clay particles were observed at the water outflow from the reservoir compared to the intake.

ACKNOWLEDGMENT

Funding for this research project was provided by the Government of the Republic of Slovenia - Ministry of the Economy and Utilities Management Company KOSTAK, Krško. This financial support is gratefully acknowledged.

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ANALIZA PROCESA IN DINAMIKE SEDIMENTACIJE SUSPENDIRANEGA MATERIALA V AKUMULACIJSKIH JEZERIH Z VISOKIMI DNEVNIMI OSCILACIJAMI

HELENA VRECL-KOJC, BOJANA DOLINAR, ROMAN KLASINC IN LUDVIK TRAUNER

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izvleček

V akumulacijska jezera z visokimi dnevnimi oscilacijami nivoja vode, kot na primer pri črpalnih hidroelektrarnah, se običajno črpa rečna voda, ki vsebuje različne koncentracije suspendiranega materiala glede na določena časovna obdobja in rečni pretok. Prispevek prikazuje analizo procesa sedimentacije suspendiranega materiala, ki temelji na interakciji med sedimentacijsko hitrostjo in gibanjem vode. Sedimentacijska hitrost grobozrnatih delcev je v prisotnosti sile vzgona funkcija velikosti sedimenta. S pomočjo laboratorijskih preiskav suspendiranega materiala iz vzorcev rečne vode so podane odvisnost velikosti sedimenta in koncentracije suspendiranega materiala glede na različni rečni pretok, odvisnost med koncentracijo suspendiranega materiala v vodi in pretokom v določenem časovnem obdobju ter razmerje med koncentracijo suspendiranega materiala in pretoka. Slednja odvisnost je kot novost prvič izražena z eksponentno funkcijo. Gibanje vode v rezervoarju z visokimi dnevnimi nihanji je analizirano s tridimenzionalnim modeliranjem tekočinskih tokov. Ocenitev rezultatov je prikazana na primeru načrtovane črpalne hidroelektrarne »Kozjak« na reki Dravi.

ključne besede

lebdeče plavine, gibanje vode, sedimentacija, transport sedimentov, črpalna hidroelektrarna, akumulacijsko jezero

ANALYSES OF THE SUSPENDED-LOAD SEDIMENTATION PROCESS AND ITS DYNAMICS IN RESERVOIRS WITH HIGH DAILY OSCILLATIONS

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Abstract

The river water pumped into reservoirs with high daily oscillations, e.g. at pumping hydroelectric power plants, contains different amounts of suspended load depending on the time period and the river's discharge. This paper presents an analysis of the suspended-load sedimentation process that is based on the interaction between the sedimentation, i.e., the settling, velocity and the motion of the water. The settling velocity of spherical particles in the presence of a buoyancy force is a function of the particle size. Laboratory investigations of the suspended material from the river-water samples have determined the ratio between the particle size and the concentration of suspended material with respect to the river discharge, the ratio between the concentration of suspended material in the water and the discharge, and the relationship between the concentration of suspended material and the discharge of water, which is for the first time expressed as an exponential function. The motion of the water in the reservoirs with high daily oscillations is solved by the three-dimensional modeling of the liquid streams. The evaluation of the results is presented for the case of the planned Kozjak pumping hydroelectric power plant on the River Drava.

keywords

suspended load, water motion, sedimentation, sedimentation transport, pumped hydroelectric power plant, reservoir

1 INTRODUCTION

The reservoir system of a pumping power station subjected to high daily oscillations of the pumped water is a place where the sedimentation process of suspended material is a continuous procedure with specific dynamics.

The sedimentation processes in reservoirs and lakes have been reported by many authors, e.g. (Graf, 1984; Fan and Morris, 1992; De Cesare et.al., 2001). In recent years, experimental and numerical model research has been performed by developing a moving boundary model of the deltaic sedimentation in lakes and reservoirs that captures the co-evolution of the river-delta morphology and the associated deposit (Kostic and Parker, 2003). One-dimensional numerical modeling of reservoir sedimentation proposed by Toniolo and Parker (2003) is a simplified model of sand-bed rivers that predominantly transport two grain sizes, sand as a bed material and mud as a wash load, where it is developed and tested as an integral, physically based moving-boundary model that captures the evolution of the river-delta deposit. The three-dimensional reservoir-sedimentation model developed by Campos (2001) is based upon Navier-Stokes equations for incompressible flow to obtain the flow field through the reservoir, and the suspended sediment transport through the reservoir was modeled with the 3D Advection-Diffusion equation.

In this paper the analysis of the suspended-load sedimentation process is performed by a settling velocity and the motion of the water in reservoirs with high daily oscillations. The dynamics of this process depends on the interaction between these two velocities. The settling velocity of spherical particles in the presence of a buoyancy force (Batchelor, 1967; Lamb, 1994) is a function of particle size; therefore, the intention of a laboratory investigation of the suspended material was to investigate different correlations between the particle size, the concentration of suspended material, and the water discharge. The motion of the water in the reservoirs with high daily oscillations is solved by the three-dimensional modeling of liquid streams based on physical models in the scope of numerical algorithms using "Fluent" software (Fluent 6.2, 2005).

Finally, the evaluation of the results is expressed for the case of the planned pumping hydroelectric power plant that is located on the River Drava within the Kozjak region near Maribor. It will be composed of three main parts: an engine house, a water-storage reservoir, and the pipeline that will connect the engine house and the reservoir. The engine house will be located near the River Drava, the reservoir on the 700-m-higher plateau of mountain Kozjak, and the pipeline some ten meters under the eastern slope of Kozjak (Fig.1a). The upper reservoir on the top of the Kolar hill will have a capacity of approximate 3 millions m^3 and lies with the bottom of the embankment, at 975 m, and the top of embankment, at 996 m above sea level, which allows 20 m of water-height oscillation. The entire inner surface will be water-resistant asphalted; at the top of the embankment there will be a maintenance road (Fig.1b).

For this case the laboratory investigations of the suspended material were established in order to achieve an evaluation of the proposed model based on a determination of the quantity of solid materials from the River Drava water and its structural determination. The results were evaluated together and gave an approximate estimation of the sedimented material in the reservoir during the exploitation period per year (Trauner and Vrecl-Kojc, 2007; Trauner et.al. 2008).

2 RESEARCH METHODS AND THE RESULTS

2.1 LABORATORY INVESTIGATIONS OF SUSPENDED MATERIAL

During the period from October 2005 to June 2007, 17 samples of water were collected with the intention of separating the suspended material for further investigations. At the same time the discharge from the River Drava was measured.

The separation of the suspended material and the water was carried out with the help of the sedimentation of particles by centrifuging and water evaporation (Table 1). The chosen approach required a lot of time, but it enabled us to determine the quantity of suspended material very precisely and to collect enough material for further investigations.

Figure 1a. Draft of the Kozjak hydroelectric power plant.

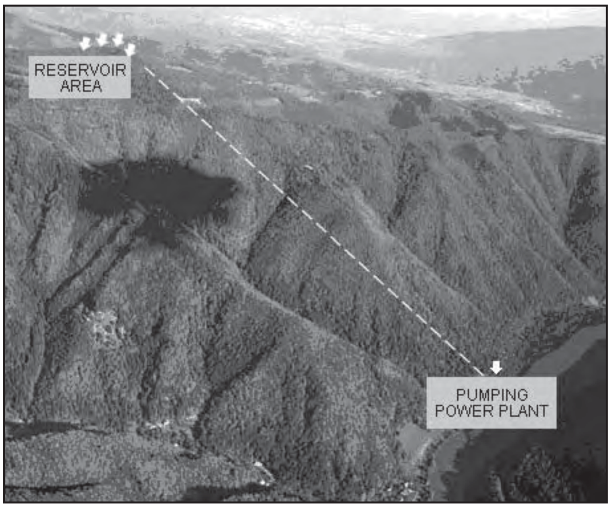

Figure 1b. Visual simulation of the Kozjak reservoir.

Table 1. Time of sampling, temperature of water (T), discharge (Q), concentration of suspended load (c).

Sample	Date	T (°C)	Q (m^3/s)	c (g/m^3)
1	23. 09. 2005	13.3	265	11.4
2	07. 10. 2005	16.6	801	187.4
3	25. 10. 2005	13.0	286	4.9
4	08. 11. 2005	13.0	234	3.4
5	29. 11. 2005	12.0	243	3.1
6	14. 12. 2005	12.5	212	2.6
7	22. 03. 2006	9.5	205	0.3
8	31. 03. 2006	9.5	293	19.1
9	05. 05. 2006	10.0	403	8.6
10	23. 05. 2006	10.0	551	25.2
11	31. 05. 2006	10.0	565	28.6
12	29. 06. 2006	10.0	488	21.1
13	10. 08. 2006	9.5	424	26.0
14	19. 09. 2006	9.5	486	13.7
15	06. 10. 2006	7.0	443	10.3
16	06. 03. 2007	9.0	289	2.6
17	07. 06. 2007	10.0	451	20.2

The results of the investigations showed that the concentration of suspended material in the water strongly depends on the discharge of the River Drava (Fig. 2). In the case when the river discharge does not exceed 750 m^3/s, this relationship can be expressed as an exponential function:

$$c = 0.4019 \cdot e^{0.0079Q} \qquad (1)$$

During a few short periods of time the discharge exceeded 750 m^3/s; in the years 2005-2007 it happened three times for periods of one or two days. In those cases the exponential function does not assume real values for the concentration of the suspended material, instead of this the proposed values approach the asymptote, which is about 240 g/m^3 of suspended material. Fig. 2 shows this case with the dashed curve.

During the project the following extremes of discharge and suspended material were observed: maximum, in October 2005 (Q = 801 m^3/s; c = 187.4 g/m^3), and minimum, in March 2007 (Q = 205 m^3/s, c = 0.3 g/m^3).

The grain size distributions of the tested solids are shown in Fig. 3. It is clear that the suspended material mostly has the size of silt, and only 6 % (weight %) of the grains belong to the clay fraction. Fig. 4 (next page) shows the ratio between the concentration of suspended material and the size of the particles (D) with respect to the discharge.

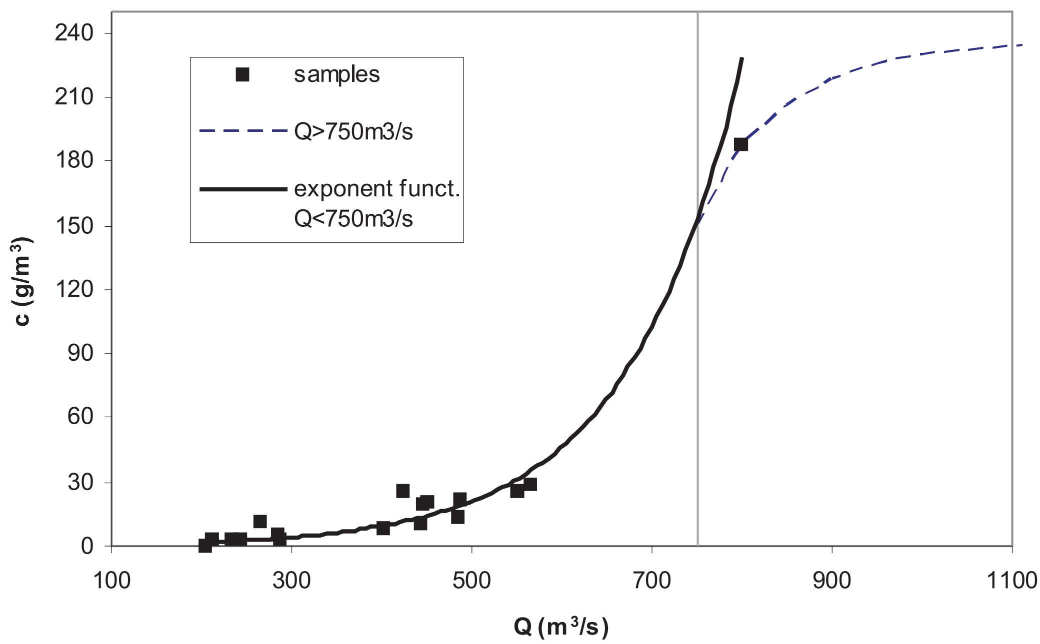

Figure 2. Relationship between the concentration of suspended material and the discharge of the water.

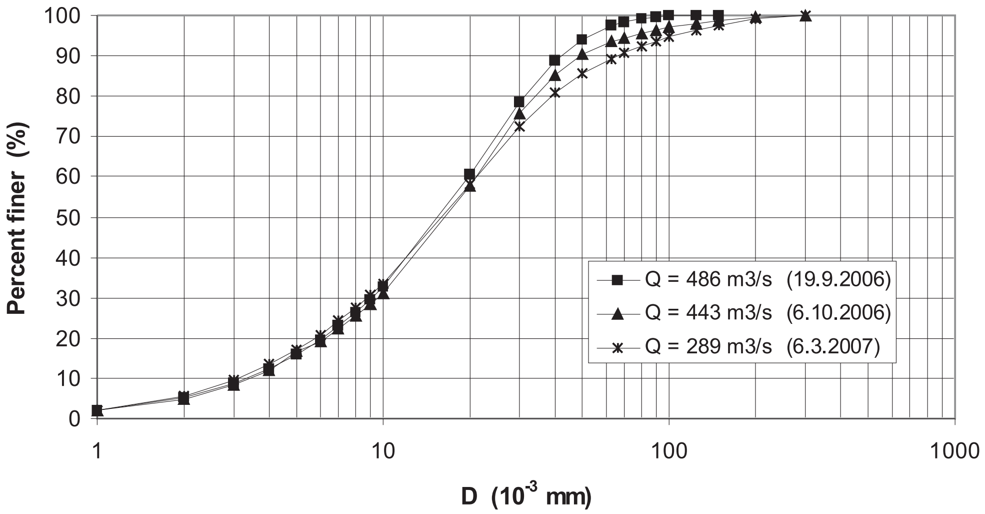

Figure 3. Grain size distribution.

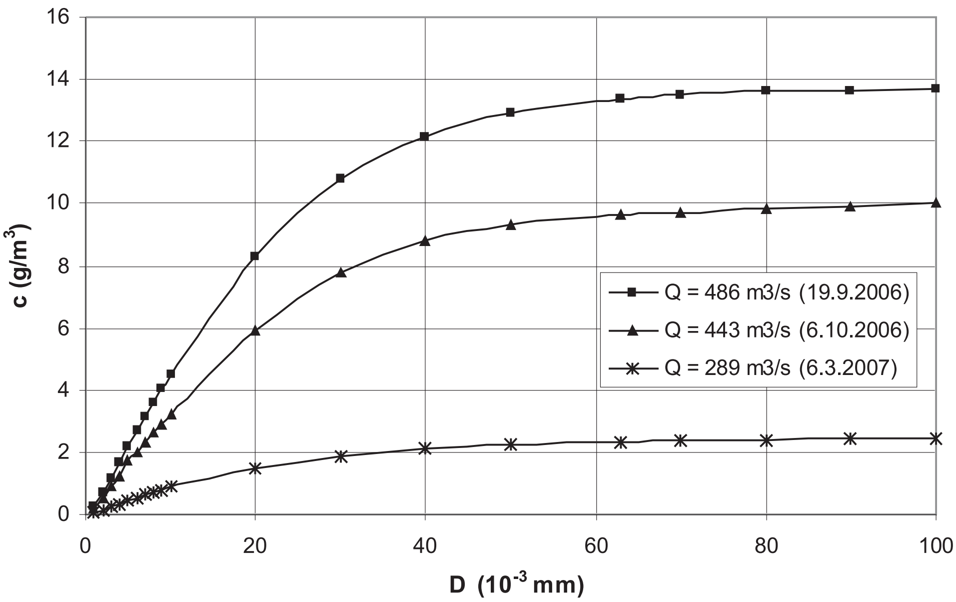

Figure 4. The ratio between the concentration of suspended material and the size of the particles with respect to the discharge.

2.2 SETTLING VELOCITY UNDER DIFFERENT CONDITIONS USING STOKES' LAW

The aim of the analysis was to determine the influence of different prepositions on the quantity and space distribution of the sediments on the bottom of the reservoir and consider the following: the grain size analyses, the relationship between the concentration of the suspended load and the discharge of the water, the settling velocity of the spherical parts in a still stream and in turbulent water with regard to the vectors of water motion expressed as position function and temperature rates (Morris and Fan, 1998). The water motion depends on the position point that is expressed as a vector function of time. The limitations and suppositions are as follows: the short time period of the investigation; the analysis was solved by a simplified hydro-dynamic method; the forms and sizes of the sediments should conform to the spherical form of the particles; and the diameter should be equivalent to the real shape of the sediment (Mott, 2000).

The settling velocity of fine particles is assumed to be as follows. In the case when a viscous fluid with spherical particles flow with a velocity that gives a Reynolds number Re < 1 (Rott, 1990), or when the particle moves through the still stream viscous fluid, the resistance force is acting on a spherical particle. Stokes' law with Eq. 2 is valid for a range of diameters, 0.2 μm to 100 μm.

The settling velocity (v_s) of the fine spherical particles in a laminar flow is given by (Lamb, 1994):

$$v_S = \frac{(\rho_S - \rho_T)}{18 \cdot \mu_T} \cdot g \cdot D^2 \qquad (2)$$

where ρ_S is the density of the spherical particles, ρ_T is the density of the water at temperature T, g is the acceleration of gravity and μ_T dynamical viscosity of the water at temperature T (see Table 2).

Table 2. Approximate values of the water's physical properties at different temperatures.

T (°C)	ρ_T (kg/m³)	μ_T (Ns/m²)
0	1000	1.790×10^{-3}
5	1000	1.510×10^{-3}
10	1000	1.310×10^{-3}
15	999	1.140×10^{-3}
20	998	1.000×10^{-3}
25	997	0.891×10^{-3}

The ratios between the grain size for fine spherical particles and the settling velocity of the suspended material in the water with regard to the temperature used in Eq. (2) are shown in Fig. 5.

The settling velocity of rough spherical particles, larger than 200 μm in the presence of a buoyancy force is given by (Lamb, 1994):

$$v_S = \sqrt{\frac{4 \cdot D \cdot g}{3 \cdot C_D} \cdot \left(\frac{\rho_S - \rho_T}{\rho_T}\right)} \qquad (3)$$

For laminar flow the drag coefficient of spherical particles (C_D) needs to be considered with:

$$C_D = \frac{24}{\text{Re}} \qquad (4)$$

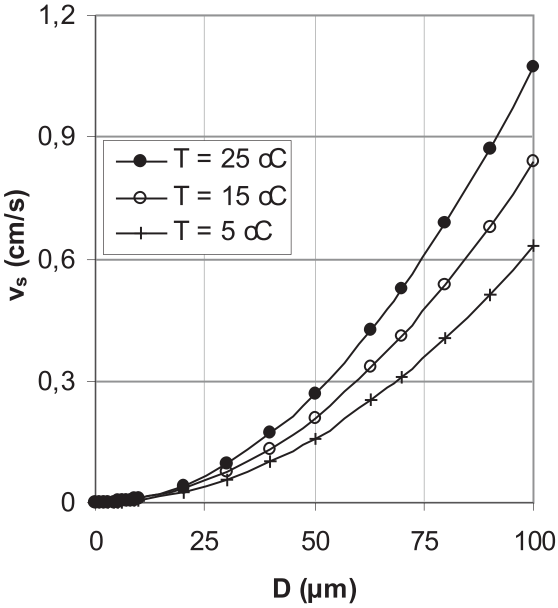

Figure 5. Relationship between the grain size of the fine suspended material and the settling velocity.

For turbulent flow the drag coefficient for the natural shape of particles cannot be expressed in an analytical form. The settling velocity needs to be determined experimentally. In the case of simplifying the real shape into the equivalent diameter of a spherical part and with the Reynolds number Re > 1000, the drag coefficient of spherical particles can be taken as the constant $C_D = 0.4$ (Lamb, 1994).

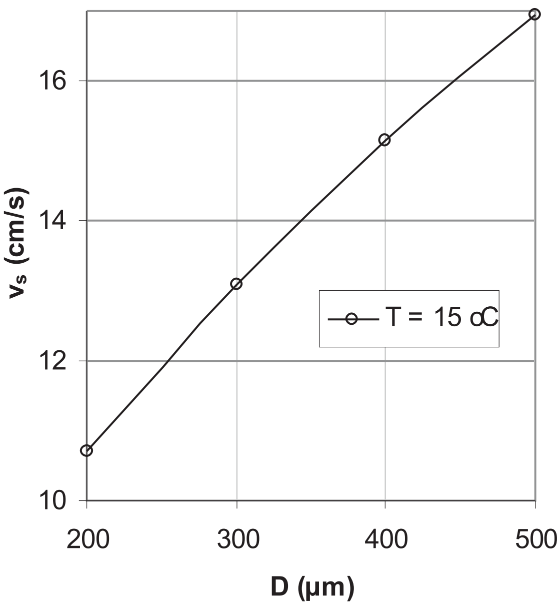

Figure 6. Relationship between the grain size of the rough suspended material and the settling velocity.

It is assumed that the particles bigger than 200 μm will sediment in the reservoir near the inflow-outflow chamber, so there is a probability of washing out these particles through the pipeline. The grain size distributions of the tested solids (Fig. 3) show that the quantity of particles of this size is less than 1%.

2.3 STUDY OF THE WATER MOTION IN THE RESERVOIR

An analysis of the water-flow velocity was performed with computer software for a fluid analysis named "Fluent" in a three-dimensional state (Fluent, 2005). The input parameter of this study was time, i.e., 24 hours (one day) of water motion in the reservoir: 4-hour inflow (pumping the water), 4-hour outflow (producing the electricity). The intention and scope of this research were to discuss two conditions that will occur during the exploitation phase in the reservoir: turbulence state, and the laminar state. The aim of the analysis was to determine the influences of each state on the velocities of the sediments.

The results present an estimation that forms a basis for evaluating the quantities of sediments according to the time period. Fig. 7 shows the results from a hydrodynamic numerical analysis of water behavior during the exploitation conditions in the reservoir (water inflow).

In addition, a quasi-stable CFD Simulation at Three Different Water Depths was also performed. In these analyses the emptying of the reservoir at three different depths was quasi-stationary observed. The simulations were achieved using the "Fluent" program. In particular, the currents in the reservoir were determined. Both, the scalar and vector velocities, were calculated with the help of numerical models. A complete 3-dimensional analysis was accomplished at a depth of 3 m (Fig. 8 and Fig. 9).

The simplified simulations cover in detail the following: the networking of the storage reservoir for three different depressions (3, 12 and 19 m), the definition of the simplified physical boundary conditions (volumetric flow rate at the emptying channel: 48 m^3/s, ambient pressure at the flat water surface), the single-phase simulation of the quasi-stable flow state, and the results in the form of the velocity vectors, the shear stress distribution as well as the streamlines.

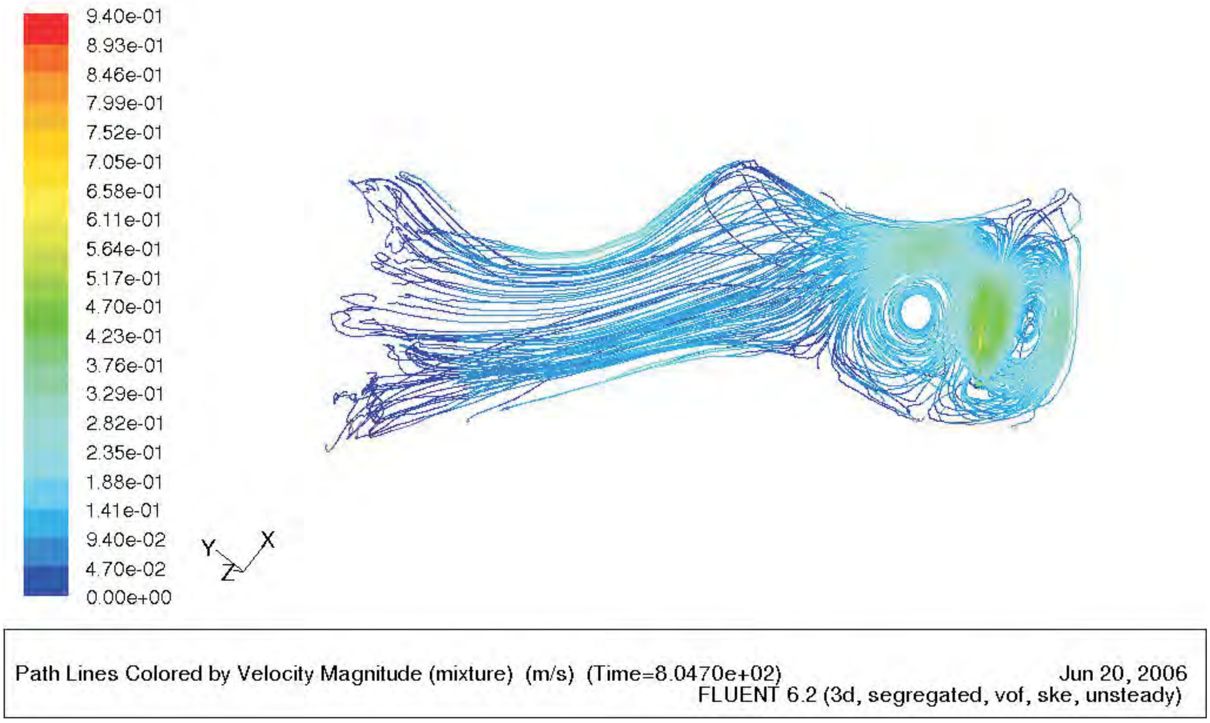

Figure 7. Results of the hydrodynamic numerical analysis of water inflow in the reservoir.

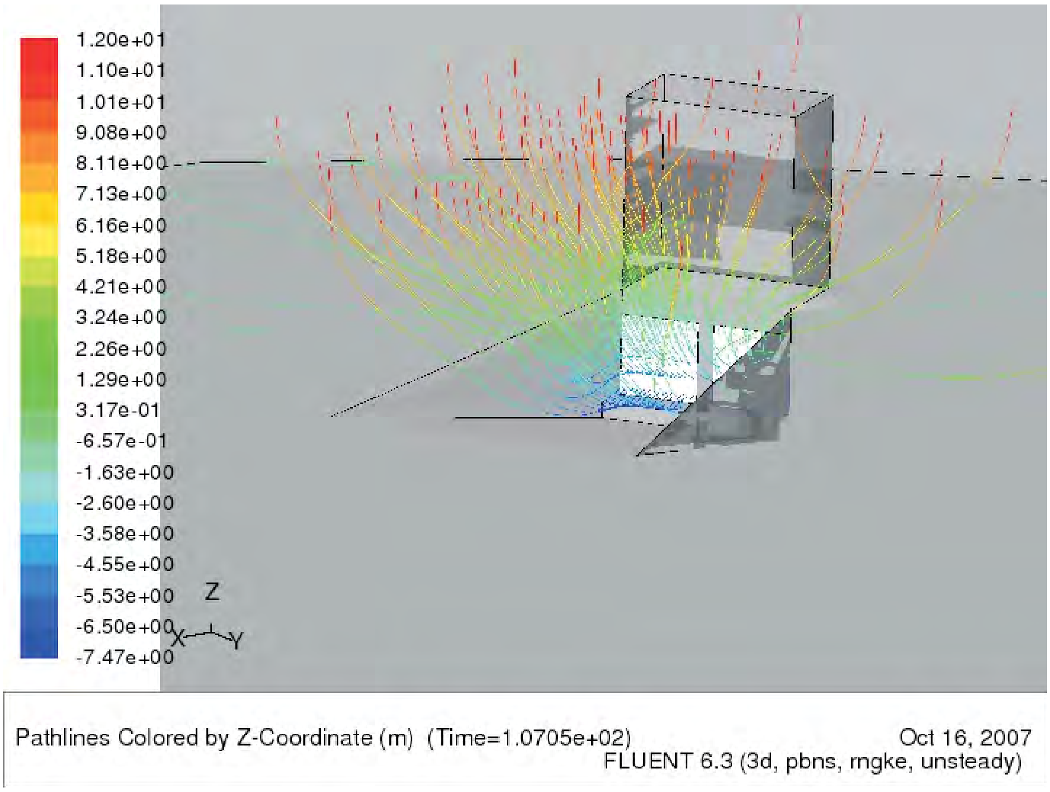

Figure 8. The distribution of velocity at the inflow-outflow chamber: water inflow in the reservoir.

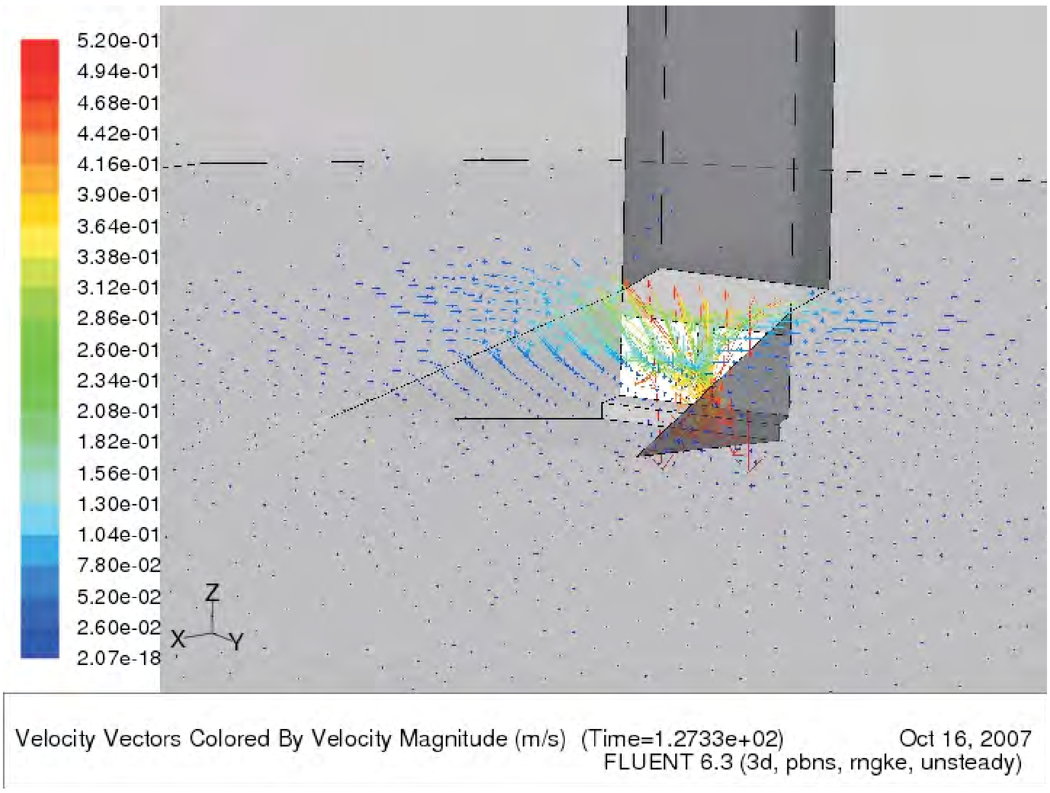

Figure 9. The distribution of velocity at the inflow-outflow chamber: water outflow from the reservoir.

3 EVALUATION OF THE RESULTS

The quantity of sedimented material in the reservoir is evaluated on the basis of the data on water flow rates for HPP Fala on the River Drava for a period of one year (September 2005 - August 2006). The size of the surface integral under the curve Q represents the water flow rate for this period, which amounts to $Q_{year} = 8.75e^9$ m^3/year (Fig. 10).

The concentration of suspended material in relation to the actual daily flow rates in the selected time can be calculated with Eq. (1). The size of the surface integral under the curve c shows the total concentration of suspended material in the River Drava, which is c_{year} = 2962.06 g/m^3/year (Fig. 10).

The discharge of the water at the reservoir inflow-outflow chamber takes 47 m^3/s and the daily time of pumping the water into the reservoir lasts 14 hours. Considering these two suppositions, and the daily concentration of suspended material of water at HPP Fala on the River Drava, the estimation of the daily quantity of sedimented material in the reservoir is achieved. Finally, the yearly quantity of sedimented material in the reservoir is estimated to be 7017 tons/year. The evaluated density of the suspended particles is 1750 kg/m^3; therefore, the total quantity of sedimented material on the reservoir bottom takes approximately 4010 m^3 per year, which with regard to the water-storage volume represents 0.13 % or a 5.6 cm thick layer per year, if it is assumed that all the material will be sedimented on 2/3 of the area of the lake bottom, which is a total of 107,511 m^2.

This calculated quantity of sedimented material has to be reduced by the quantity of material that will be washed out through the pipeline during the water outflow into the River Drava.

The evaluation of the water motion in the reservoir leads ot the following remarks. The analyses have shown that the water inflow in the reservoir presents an unstable hydrodynamic process, which means that the water velocity in this stage is not constant with regard to appointed areas of the lake. It traverses from the initial turbulent state into the later laminar state. The active flow motion will be limited to the first part of the reservoir near the inflow-outflow chamber where the velocities will reach from 0.65 m/s to 0.25 m/s in two major whirls. The highest velocities of flow appear next to the inflow-outflow chamber, in the area of both embankments approach to a new, slightly increase of velocity. In the second third of the reservoir, a large number of local whirls will be present; the velocities of which will be negligibly small (0.1 m/s). In the last third of the reservoir the velocities are close to 0 m/s, the water is in general standing still with possible vertical whirls that can occur within a radius width of around 10 m. They could raise the sediments in this area; however, this would not have an influence on increasing or decreasing the material quantities in the reservoir.

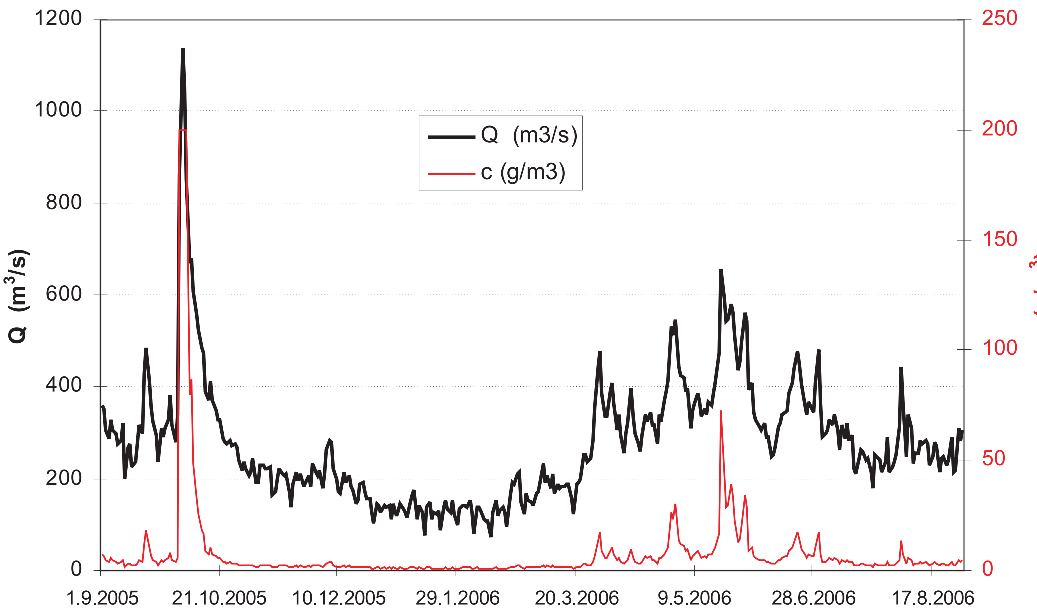

Figure 10. Water flow rate Q for the HPP Fala for the period between 1 September 2005 and 30 August 2006.

4 CONCLUSIONS

Analyses of the suspended-load sedimentation process performed by the interaction of the settling velocity and the motion of the water in reservoirs with high daily oscillations expressed the dynamics of this process. The laboratory investigation results of the suspended load of water samples taken from the river is given as the ratio between the concentration of suspended material and the size of the particles with respect to the discharge, which is an important correlation for the settling velocity of the spherical particles in the presence of a buoyancy force, because it is a function of the particle size. The investigations also gave the relationship between the concentration of suspended material and the discharge of water, which is for the first time expressed as an exponential function. The motion of the water in the reservoirs with high daily oscillations solved by three-dimensional modeling using "Fluent" software has shown that the water inflow in the reservoir represents an unstable hydrodynamic process, which means that the water velocity in this stage is not constant with respect to appointed areas of the lake. It traverses from the initial turbulent state into the later laminar state.

It is foreseen that during the exploitation conditions in the reservoir the active flow motion will be limited to the first part of the reservoir, near the inflow-outflow chamber. The highest velocities of flow appear next to the inflow-outflow chamber, in the area of both embankments there is an approach to a new, slightly increased velocity. In the second third of the reservoir, a large number of local whirls will be present; the velocities of which will be negligibly small. Therefore, the analyses of the water's motion and sedimentation have given estimation that the main part of the sedimeted material with a presumed weight of 7017 tons/year will be sedimented on 2/3 of the area of the lake.

ACKNOWLEDGMENT

The present research work is part of the project funded by the Waterpool Competence Network Water Resources and Dravske elektrarne Maribor. The numerical part of the water motion was done in cooperation with the Faculty of Civil Engineering, Graz University of Technology.

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IZBOLJŠANJE KVALITETE PODZEMNE VODE Z UVAJANJEM OGLJIKOVEGA DIOKSIDA

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izvleček

Predstavljeno raziskovalno delo obravnava razvoj sodobne metode za izboljšanje kakovosti podzemne vode z ekonomsko perspektivno uporabo ogljikovega dioksida.

Osnovna pilotna naprava za uvajanje ogljikovega dioksida je bila razvita z namenom ohranjanja karbonatnega ravnotežja v vodi, ki se črpa iz podzemlja. Optimalna količina ogljikovega dioksida, ki je naravna komponenta podzemne vode ob uporabi le-te v različne namene (pitna, tehnološka voda) nudi hkrati zaščito pred odlaganjem mineralnih oblog in preprečuje korozijo. Adaptacija obstoječe pilotne naprave je v začetni fazi vključevala testni zagon in preliminarne meritve. V nadaljevanju je bil vgrajen senzorski sistem za spremljanje najpomembnejših parametrov karbonatnega ravnotežja: pH vrednosti, temperature, prevodnosti in raztopljenega CO_2*. Sledili sta dve seriji eksperimentov z različnimi količinami dodanega* CO_2*. Kemijska sestava vode je bila analizirana s pomočjo ionske kromatografije in avtomatske titracije. Regulacija uvajanja plina je bila v prvi seriji eksperimentov volumetrična, v drugi seriji pa zaradi boljše natančnosti nadomeščena z masno regulacijo, tehtanjem plina. V začetku pretočni sistem je bil v drugi seriji zaprt glede na dotok sveže vode, z namenom doseganja večjih nihanj v sestavi vode. Sledili so eksperimenti v različnih letnih časih z namenom ugotoviti vpliv letnih časov na sestavo podzemne vode in učinkovitosti dodajanja ogljikovega dioksida.*

ključne besede

podzemna voda, kakovost pitne vode, pilotna naprava, karbonatno ravnotežje, ogljikov dioksid, obarjanje, vodni kamen

IMPROVEMENTS TO THE QUALITY OF UNDERGROUND WATER BY INTRODUCING CARBON DIOXIDE

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Abstract

The presented research work is focused on the development of an innovative way of economically improving the quality of underground water by the application of carbon dioxide.
The basic pilot plant was developed with the idea of applying carbon dioxide in order to maintain the carbonate equilibria in water, pumped from under the ground. The optimal content of this natural component in underground water, used in urban areas for different purposes (e.g. drinking water, heating systems etc), simultaneously prevents corrosion and precipitated mineral deposits.
The adaptation of an existing pilot plant started with operational testing and preliminary measurements. An appropriate sensor system for the online monitoring of the tap water's heating process measuring parameters such as the temperature, the concentration of dissolved carbon dioxide, the conductivity and the pH value was built in. Different amounts of carbon dioxide were applied during the two experimental stages. The composition of the water was regularly analysed using automatic titration and ionic chromatography. The gas-dosing control in the first phase was volumetric. Due to an observed inaccuracy in the gas-dosing system, the volumetric dosing control was replaced with a system for the mass control of the introduced gas. Closing the system was considered to be suitable, as the water composition remained almost constant during the entire experiment. Improvements to the gas-dosing control and the closing of the system were carried out in the final phase of the pilot plant's adaptation. Further measurements were made in different seasons to test the seasonal influences on underground water's composition and the efficiency of the carbon dioxide supply.

keywords

underground water, drinking water quality, pilot plant, carbonate equilibria, carbon dioxide, precipitation, scale

1 INTRODUCTION

Underground water, percolating through different geological structures, dissolves certain minerals. The behaviour of this underground water is most interesting in areas that consist of carbonate rocks, e.g. limestones and dolomites. The main minerals in these rocks are calcium and magnesium carbonates, which dissolve easily in underground water and give the water its hardness. The quality of the water depends significantly on its hardness. In urban areas underground water is widely used as a source of water for various purposes, e. g. as drinking water, sanitary water and communal water [1].

Municipal companies that manage distribution systems for underground water and wastewater are constantly confronted by the necessity to invest large amounts of money in maintenance programmes with regard to water installations and canalizations in order to prevent the consequences of limestone deposits and corrosion [2].

Healthy water for human consumption should not be corrosive in waterworks with either form limestone deposits. Therefore, the water has to be kept in a thermodynamic balance with the mineral phases of calcite or aragonite in order to fulfil this condition [3]. The natural water content depends on a combination of the geochemical and biological processes, in addition to the water's pH and alkalinity, which are two of the most important parameters affecting the composition of natural water [4].

Conventional drinking-water preparation as well as cooling and boiling feed-water preparation is based on softening and demineralization. Softening units are designed to replace of multiply charged positive ions (Ca^{2+}, Mg^{2+}) with sodium (Na^+) ions and demineralization units are designed to remove a fraction of all the ions from water [5]. A more recently developed alternative method for preventing waterworks from developing lime scale is introduction of electromagnetic water conditioning. An electromagnetic conditioner works by creating a magnetic field around the pipework, which alters the ions' crystallization behaviour, so removing their ability to form scale [6].

Drinking water pre-preparation, based on the subsequent addition of CO_2 gas as a natural component of healthy drinking water is a low-cost process for improving the quality of drinking water and, simultaneously, not altering the natural water's mineralogical composition. It represents an innovative and environmentally friendly method, as no unwanted by products or pollution arises. The aim of the presented research work was to develop a pilot plant and to test different methods for increasing the efficiency degree of the CO_2 supply. To our knowledge, the presented pilot plant and such an application of carbon dioxide are original and have never been published before.

To date a similar application of CO_2 has been developed by the Messer Company but this one is related only to wastewater neutralization. The advantage of using carbon dioxide rather than sulphuric acid is reflected in simplifying the technological process, while at the same time reducing the costs [7].

2 CARBONATE SPECIES IN NATURAL WATERS

Sedimentary rocks, such as limestones and dolomites represent the most extended rocks of aquifers and their main minerals, calcium and magnesium carbonates dissolve easily in groundwater. Consequently, calcium is found to be the highest concentration of totally dissolved solids in average river compositions from different continents [8].

With regard to the composition of natural waters, 90% of the impurities come from just eight inorganic species i.e., Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-}, and Cl^-. Some of them are inert, e.g. Na^+, K^+, NO_3^- and Cl^-, meanwhile the components of the carbonate equilibria are involved in numerous chemical reactions (1), which results in variations in their concentrations [9].

$$CO_2(g) \updownarrow$$
$$CO_2(aq) + H_2O \longleftrightarrow H_2CO_3 \tag{1}$$
$$\updownarrow \qquad \updownarrow$$
$$OH^- + H^+ \quad H^+ + HCO_3^-$$
$$\updownarrow$$
$$H^+ + CO_3^{2-} \quad + Ca^{2+} + CO_3^{2-}$$
$$\updownarrow$$
$$CaCO_3(s)$$

The slowest reaction in this dynamic system is the gas transfer into the aqueous phase, which is slower than other reactions that produce or consume carbon dioxide during the aqueous phase, e.g. calcite dissolution and precipitation. The formation of carbonic acid is reported to equilibrate within 20-200 s in a stirred solution, while the dissociation of bicarbonate and carbonate ions equilibrates within seconds [10].

Under all pH conditions, most of the dissolved CO_2 exists as CO_2 (aq) and only a small amount of the dissolved CO_2 (aq) is hydrated to produce carbonic acid [9]. Various ratios of CO_2 (aq)/H_2CO_3 (aq) have been reported e.g. 385/1 or 250/1 [11]. It is conventional to express the total dissolved carbon dioxide as H_2CO_3*, which represents the sum of the CO_2 (aq) and the H_2CO_3 (aq) [9].

The dissolved carbon dioxide in an aqueous solution is distributed among three species, H_2CO_3* (dissolved CO_2), HCO_3^- (bicarbonate) and CO_3^{2-} (carbonate). Table 1 shows the equilibrium equations and the corresponding constants over different pH ranges [8, 9, 12]:

Table 1. The carbonate equilibria equations and the corresponding equilibrium constants over different pH ranges.

pH range	Equilibrium equation	Equilibrium constant
pH < 4.3	$CO_2\,(g) + H_2O \rightleftarrows H_2CO_3^*$	$K_{CO2} = 10^{-1.47}$ atm^{-1}
4.3 > pH < 8.2	$H_2CO_3^* + H_2O \rightleftarrows HCO_3^- + H_3O^+$	$K_{H2CO2} = 10^{-6.35}$
pH > 8.2	$HCO_3^- + H_2O \rightleftarrows CO_3^{2-} + H_3O^+$	$K_{HCO3^-} = 10^{-10.38}$

The reaction between calcite ($CaCO_3$) and carbon dioxide (2), derived from biological processes, is the fundamental reaction for understanding the dissolution and precipitation of $CaCO_3$ in nature [8]:

$$CO_2(g) + H_2O(lq) + CaCO_3(s) \rightleftarrows Ca^{2+}(aq) + 2HCO_3^-(aq) \qquad (2)$$

The redundancy of the dissolved CO_2 causes the formation of a weak carbonic acid, a decrease of pH value and dissolution of $CaCO_3$. The acidic pH of drinking water has harmful influence on humans' physiological environment and causes corrosive damage to pipelines (Figure 1).

The deficit of dissolved CO_2 (degassing of water) causes the precipitation of non-soluble crystalline structures (e.g. $CaCO_3$) and results in the obturation of mechanical parts (filters, valves), flow hindrance due to limestone precipitates, and the loss of energy (Figure 2).

Rocks formed from sediments cover 93% of the Slovenia's land area. Among them limestone (25%) and dolomite (10%) are the most extensive. In Slovenia, over 95% of the water used for public supplies is drawn from groundwater, while, for example, in the United States the quantity is only 40% [3, 14].

The Drava basin, located in the Northeast of Slovenia, represents a source of potable water for the wide Maribor area. A geological map in Figure 3 shows the ground composition of the aquifer along the River Drava in the wider area of the City of Maribor. The

Figure 1. Corrosive damage to pipe lines.

Figure 2. Noxious consequences of limestone deposits.

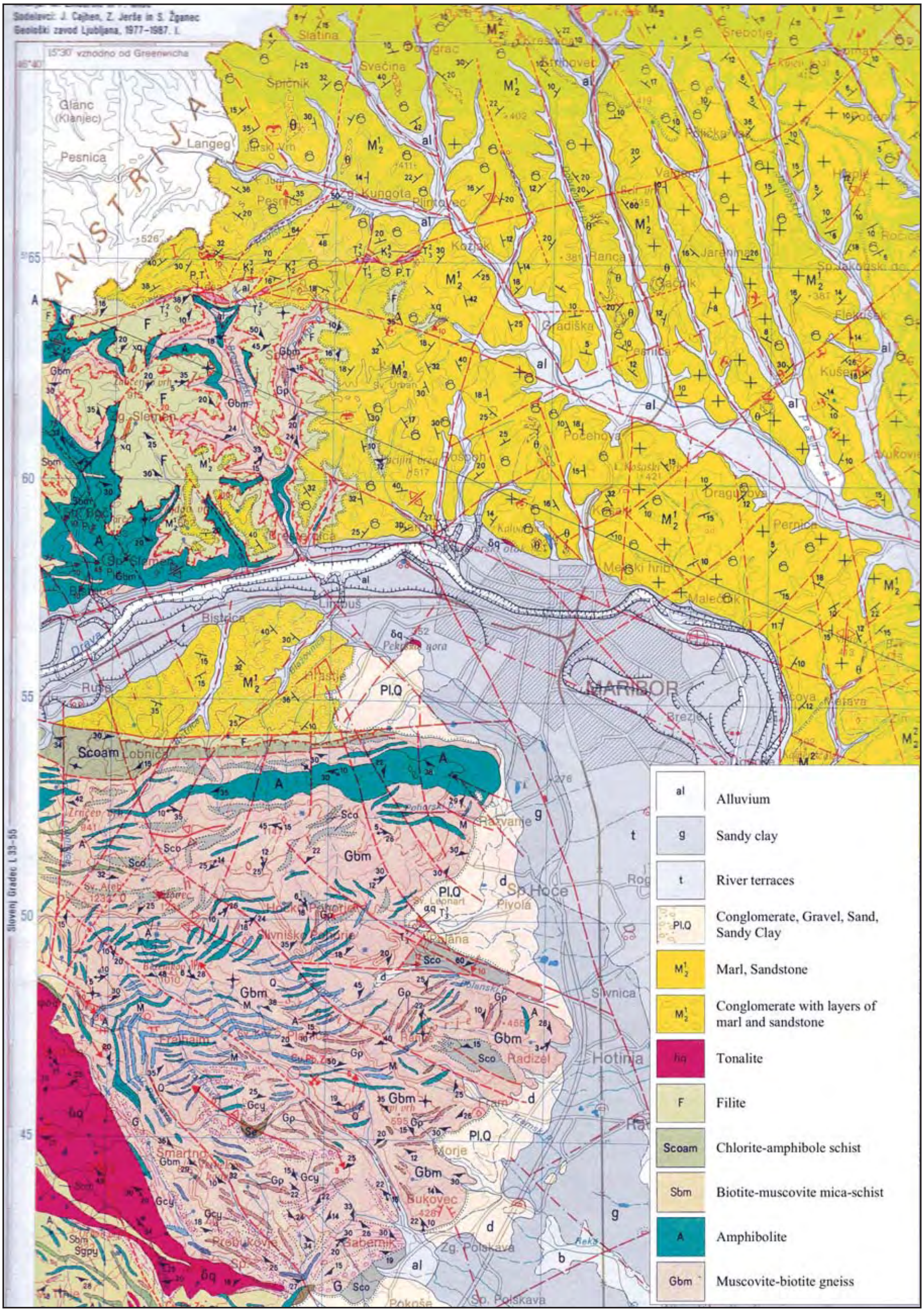

Figure 3. Geological map of the underground water area in Maribor.

underground water levels (UWL) around the pumping station at Vrbanski plateau are presented in Figure 4. The underground water level variations over the period 2004 to 2008, considering water flow and the quantity of pumped water are shown in Figure 5.

The presented international research work that discusses the optimization of underground water quality by introducing carbon dioxide was performed within the K-Net Centre of Water Resources Management (WRM).

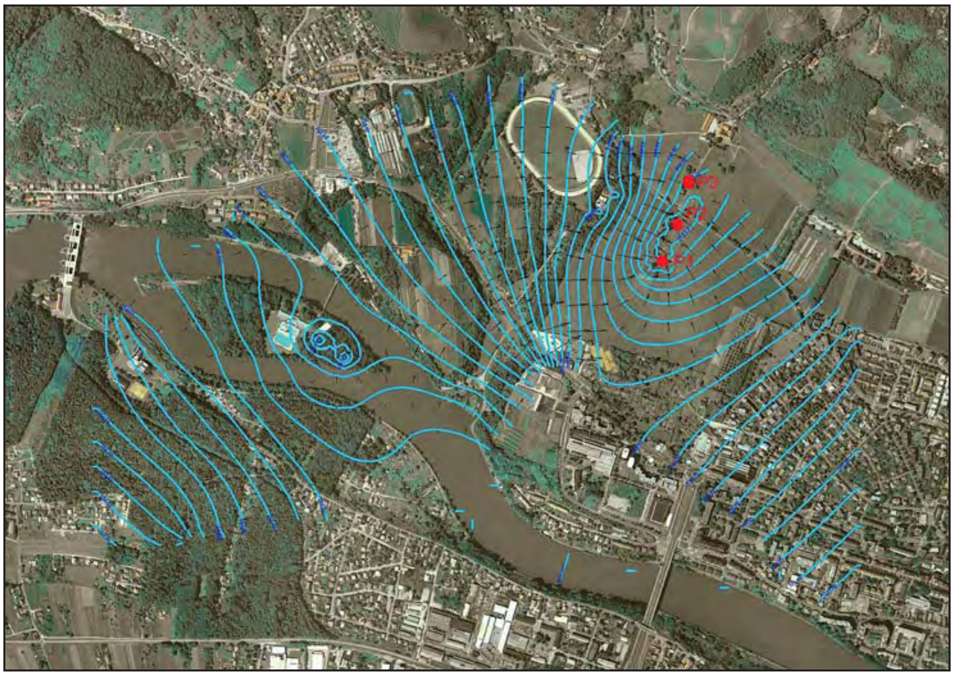

Figure 4. Underground water levels (UWL) in the area of Vrbanski plateau, the pumping station for Maribor waterworks.

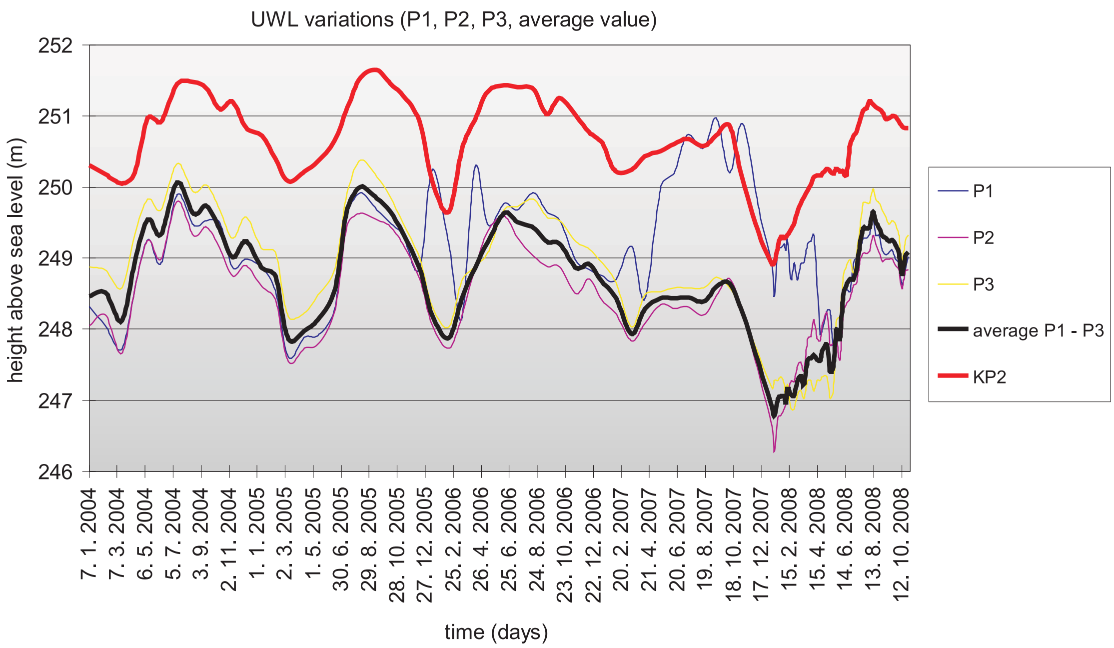

Figure 5. The underground water-level variations over the past four-year period (2004 to 2008) considering the water flow and the quantity of pumped water.

Table 2. The average values of significant carbonate equilibria parameters regarding drinking water over a ten-year (1995 -2005) period in the Maribor area.

	Winter	Spring	Summer	Autumn
Ca^{2+} ($mg \cdot L^{-1}$)	76.17	81.28	54.35	73.81
HCO_3^- ($mg \cdot L^{-1}$)	265	273	248	251
pH	7.52	7.53	7.47	7.57
Conductivity ($\mu S \cdot cm^{-1}$)	516	511.25	510.62	511.16

The aquifer is classified as a carbonate-silicate type with inter-grained porosity and belongs to the second most extended of the Slovenian aquifers' types (26.2%) [15]. Analytical data, including the averages of the past ten years characterize the tap water in the Maribor region as moderately hard water (12–18 °n) [16]. Comparing the ten-year averages of water composition over different seasons indicates some typical patterns in the most significant parameters of carbonate equilibria (Table 2) [16]. The total dissolved solids concentration (TDS), including the concentration of Ca^{2+}, Mg^{2+} and CO_3^{2-} is increased in the spring and winter seasons due to more intensive rock weathering and washing out. Meanwhile, the pH value does not vary significantly over the year.

3 EXPERIMENTAL

The experiments were performed on a pilot plant constructed for the observation of precipitation in pipe-lines and heat exchanger. The basic pilot plant consisted of a closed primary pipeline with adjustable temperatures of the heating fluid and an open secondary pipeline, supplied by tap water, a heat exchanger, and an ultrasonic stirrer.

An operational test was performed to find out the initial time for the stabilization of the system, and to indicate the scale precipitation in the heat exchanger under the following conditions: 65°C, 2 bars and 2 L/min of water flow, known tap-water composition, applied ultrasound (US, 27 kHz, 4W), and without introducing additional carbon dioxide.

A preliminary set of measurements was carried out on the basic pilot plant, without the sensor system. The samples were taken periodically every hour at five points of the process. The concentrations of free carbonic acid, calcium ions and hydrogen carbonate ions were determined titrimetrically. The temperature and the pH value were measured, while the pressure and water flow were kept constant during the entire experiment. Other experiments were performed using the same pilot plant, operating under the same conditions, but with the application of different amounts of additional carbon dioxide [14].

The new sensor system and the corresponding software package were chosen on the basis of the preliminary results. During the first adaptation phase, a new sensor system (Figure 6) for online monitoring of the dissolved carbon dioxide, the pH, the temperature and the conductivity were built in and calibrated. The disadvantage of this, the only appropriate sensor system, is that it makes it possible to control the mentioned parameters only within a limited temperature range. The CO_2 electrode characteristics make it possible to measure the amount of dissolved CO_2 within a temperature range up to 65°C and within a concentration range from 0 to 4000 mg/L. The heat exchanger was also replaced with a new, gasketed one.

Figure 6. Sensor system with electrodes.

The pilot plant after the first phase of adaptation is presented in Figure 7.

The first set of experiments was carried out in the summer season. It comprised 35 measurements: seven at each of five measuring points (MP), with the addition of different amounts of CO_2 (1 L/min, 3 L/min and 5 L/min), and all with and without the application of

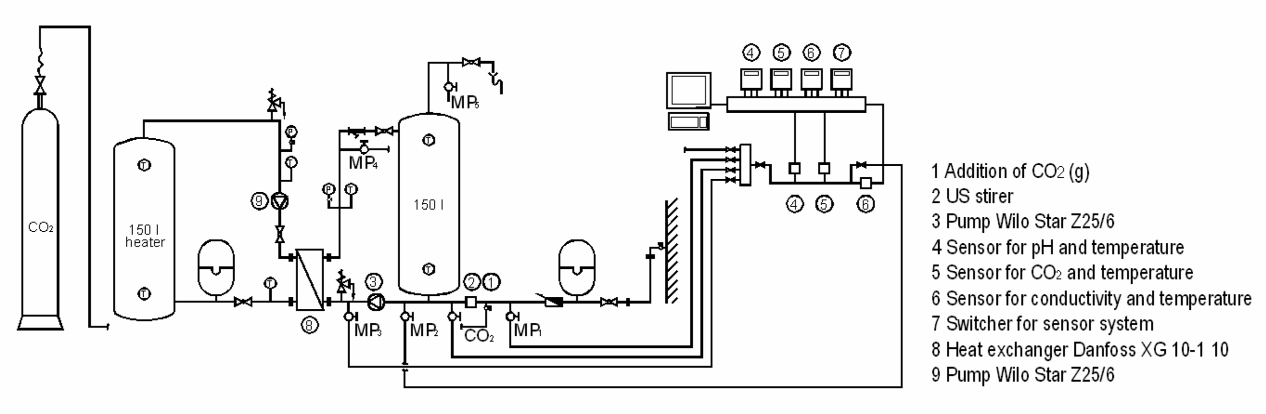

Figure 7. Partially adapted pilot plant.

ultrasound. The temperature, the amount of dissolved carbon dioxide, the conductivity, and the pH value were measured online. During this set of experiments, some inaccuracy was observed in the volumetric dosing control of the carbon dioxide. Therefore, an additional adaptation of the CO_2 dosing system was necessary.

To improve the dosing accuracy of the additional gas into the system, the non-return valve was replaced with a new one and an additional gas reservoir was built in as a buffer (Figure 8). The mass of gas introduced became controllable on the basis of measurements of the gas weight (Figure 9). The reduction valve on the tap line was also changed and an additional overflow valve was built in at the outflow of the experimental line, in order to maintain the pressure in the system at a constant value.

One measuring point in the system became sufficient, operating under close conditions (regarding water). The former measuring point four (MP 4) was chosen as the most appropriate.

The water samples were further analysed using automatic titration (Metrohm GP Titrino 736) and ionic chromatography (Dionix ICS – 3000 DC, DX - 500).

The second, i.e. winter, set of experiments was carried out on the adapted pilot plant, operating as a closed system with mass control of the gas dosing. This set comprised nine experiments: five with and four without the application of ultrasound (US) with the addition of different amounts of CO_2 (25 g, 50 g, 100 g, and the maximum amount, 240 g), which finally resulted in 65 water samples. The maximum amount of introduced gas was determined experimentally and depended on the application of ultrasound. Without ultrasonic stirring the amount of introduced gas corresponded to the solubility limit of CO_2 in water. In the case of applied ultrasound the non-dissolved gas was leaving the aqueous system due to stirring and its introduction did not stop spontaneously. The process temperature during the winter set of experiments was between 60 and 65°C due to working-temperature limitation of the sensor system.

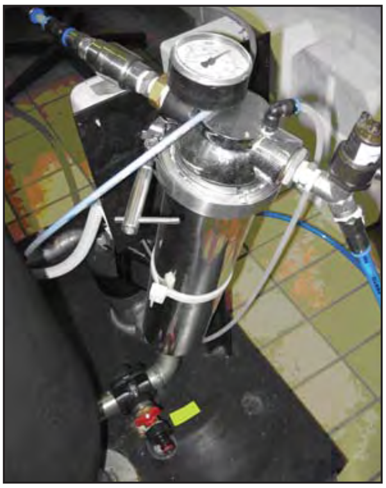

Figure 8. The additional gas reservoir.

Figure 9. Weighting of the introduced gas.

The detailed water-composition analyses for all the water samples followed the work on the pilot plant.

The software package "PHREEQC-2" was selected as the relevant program for the hydro-chemical modelling and Langelier saturation indexes were determined on the basis of the collected experimental data for the second experimental set.

4 RESULTS AND DISCUSSION

Preliminary and test measurements were carried out on the basic pilot plant to test the operating conditions of the plant and the experimental proceedings. The early phase was focused on the adaptation of the plant, and the selection and purchasing of an appropriate sensor system.

During the preliminary experiments carried out without the sensor system, it was established that the operating conditions are stabilized over a period of two hours. When the system operated without introducing additional carbon dioxide, the measured concentrations of calcium ions at the measuring points MP 1 and MP 3 were about 10% higher than the equilibrium concentrations (evaluated from a thermodynamic diagram of the calcium carbonate solubility vs. temperature and pH). A slight over-saturation was already present at the entrance and this increased during the heating, resulting in abundant scaling on the heated surfaces. The output concentrations were comparable to the equilibrium values. The additional application of carbon dioxide between measuring points MP 1 and MP 2 resulted in an increase in the concentrations of free carbonic acid, and a decrease in the pH value. The results from the next three measuring points (MP 3 to MP 5), which showed a decrease in free carbonic acid concentration and a slight rise in the pH compared to MP 2, are probably related to transferring the gas into the aqueous phase [14].

The extensive experimental work presented in the next paragraphs was performed in summer and winter of 2006 and 2007. Due to large amount of experimental data only some representative data are discussed in this paper.

After the sensor system was built-in and calibrated, the first, summer set of measurements was performed using on-line monitoring of the most relevant carbonate equilibria parameters. Considering the results of the water-composition analyses, the open system, operating at temperatures between 18 and 58°C without the introduction additional carbon dioxide, displayed only slight signs of the expected behaviour. As the temperature increases, the concentration of CO_2 decreased by 12% and the pH value increased by 2%, from the initial values (Figure 10). Based on slight changes in the Ca^{2+} ions content (a decrease of 0.5% at MP 3) it might follow that the over-saturation of the water involved is relatively low.

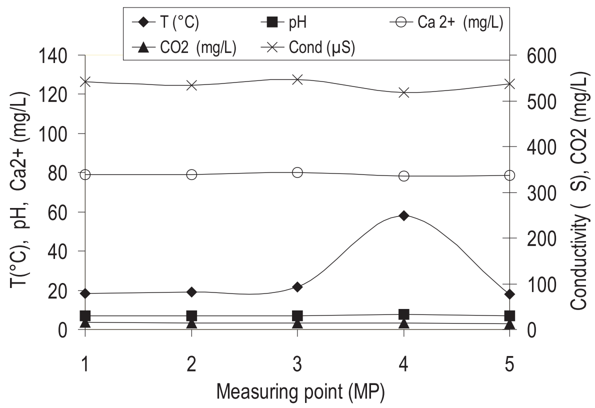

Figure 10. Measurement results without applied US and without introducing additional CO_2 (open system).

The measurement results with 5 L/min of introduced carbon dioxide without the applied ultrasound are presented in Figure 11.

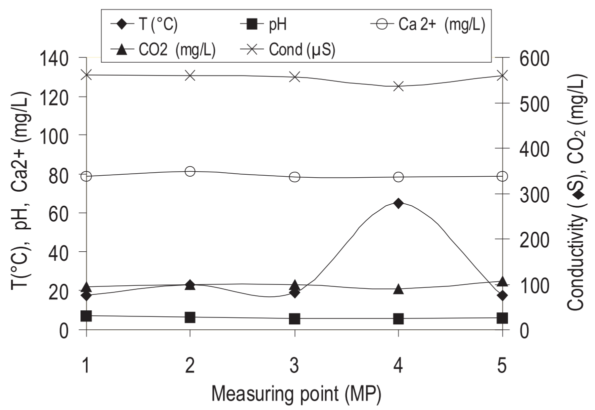

Figure 11. Measurement results without applied US and with introducing 5 L/min of additional CO_2 (open system).

Carbon dioxide was applied between MP 1 and MP 2, which resulted in a 3% increase in the concentration of dissolved carbon dioxide and a 26% decrease in the pH value at MP 3. The calcium- ions content decreased due to precipitation (0.08%). The result from the last measuring point, MP 5, which shows a rise of 0.1 units of pH compared to MP 3, is related to the transferring of the gas into the aqueous phase. The concentration of calcium ions increased by 2.5%, as the temperature decreased to approximately 50°C and this could indicate that the precipitated calcium carbonate was partly dissolved again. The terminal pH value remained within a slightly acidic range (5.93).

The same experiment was carried out with the application of an ultrasonic stirrer. The application of ultrasound was indicated by the 20% increase in the initial amount of dissolved carbon dioxide at MP 5 as a consequence of the ultrasonic stirring.

Based on the water analyses results and the changes of water composition during the experimental process, a more detailed study and description of the system followed.

They showed that the composition of the water did not alter significantly during the whole of the experimental period. A possible explanation for this in the presented investigation phase was that the kinetic conditions did not allow precipitation in this open system, although the system was over saturated from the thermodynamic point of view. The extracts from wider water composition analyses, carried out by the automatic titration and ionic chromatography, are presented in Tables 3 and 4. It turned out that no significant variations in the calcium content occurred with process temperatures up to 65°C. The maximum analysed variation in the calcium content was only 2.66 mg, i.e. 3.6% of the initial value.

This led to the idea of closing the system (in terms of freshwater inflow) in order to intensify the precipitation process and to examine the effect of different amounts of additionally introduced carbon dioxide.

The second, i.e. winter set of measurements was carried out on the pilot plant, operating as a closed system in terms of fresh water inflow. The overview of the experiments showed that the optimal quantity of applied carbon dioxide for the operating conditions and the used tap-water composition used is 500 mg. The experimental procedure and the measurement data without introduced gas, with the application of 500 mg of carbon dioxide are presented in the following Figures 12 and 13, respectively.

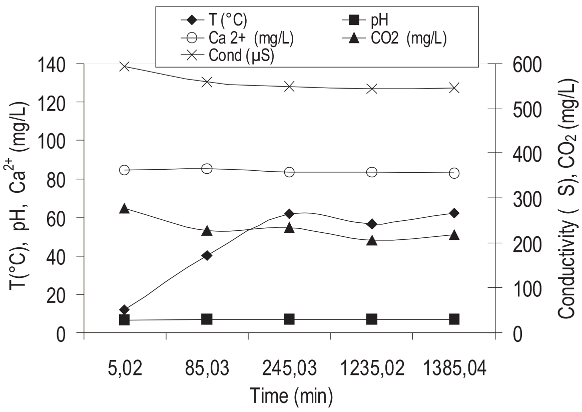

Figure 12. Measurement results without applied US and without introducing of additional CO_2 (closed system).

Table 3. Water composition analyses results without applied US and without additional CO_2.

	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)	alkalinity (ml HCl)
MP 1	n. a.	n. a.	n. a.	78.95	19.87	17.24	30.28	281.56	4.61
MP 2	13.28	2.07	15.22	78.88	19.55	15.68	30.31	284.04	4.65
MP 3	14.35	2.20	15.58	80.26	21.16	19.02	32.12	288.49	4.73
MP 4	13.01	2.14	15.37	78.15	19.58	18.23	30.53	282.19	4.62
MP 5	13.01	2.08	15.45	78.58	19.74	17.34	31.06	280.68	4.60

Table 4. Water composition analyses results without applied US and with 5 L/min of additional CO_2.

	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)	alkalinity (ml HCl)
MP 1	13.07	2.23	15.37	78.88	20.35	17.74	31.49	282.14	4.62
MP 2	13.68	2.32	15.53	81.38	21.60	17.82	33.01	291.41	4.78
MP 3	13.24	2.23	15.15	78.24	19.91	17.55	30.68	281.18	4.61
MP 4	13.19	4.26	15.00	78.48	22.22	18.11	31.05	282.02	4.62
MP 5	13.24	2.23	15.20	78.80	21.23	19.13	31.60	279.62	4.58

The system was stabilized and the terminal temperature of 62°C was reached in a period of four hours because the initial water temperature was only 11.8°C due to the winter season. During the heating the CO_2 concentration of decreased by 42.8 mg/L (15.4% of the initial value) and consequently the pH value increased by 0.43 units (6.3% of the initial value). The variations in Ca^{2+} concentration during the process were expected, but were not significant. The highest Ca^{2+} concentration (85.1 mg/L) was reached at 40°C, and it decreased by 1.8 mg/L (2.1% of the initial value) until the terminal temperature was reached. The variations in the dissolved species showed that, also in the closed system, operating at a temperature of 62°C meant that only slight precipitation was present.

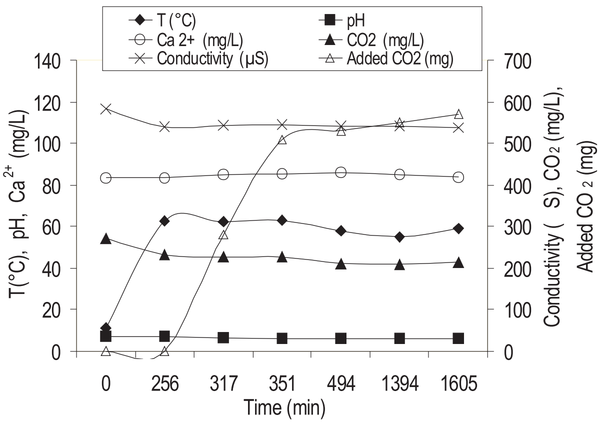

Figure 13. Measurement results without applied US and with introducing 570 mg of additional CO_2 (closed system).

In the case of introducing 570 mg of additional CO_2 the initial temperature was 11.1°C (winter season). The system reached the terminal temperature (63.1°C) after 256 minutes of heating, when the introduction of additional gas started. The added gas caused a drop in the pH value, which after the introduction of 280 mg of CO_2 decreased by 0.74 units (10.3% of initial value). The lowest pH value (6.06) was reached after the addition of 550 mg of gas, when the initial value was decreased by 1.11 units (15.3% of initial value). As expected, analyzing the contents of the Ca^{2+} ions, less significant variations were noticed. The content of Ca^{2+} decreased only by 0.2 mg/L (0.25% of initial value), when the system was heated to the terminal temperature (63.1°C). During the introduction of the additional gas, the Ca^{2+} concentration increased and reached a maximum value of 86.2 mg/L (103% of initial value) after 494 minutes, when 530 mg of gas was introduced. The initial Ca^{2+} concentration was exceeded at that point, which showed that the existing mineral deposits were dissolved. The experiment was concluded after 1605 minutes (26.75 hours), when the Ca^{2+} content reached 100.35% of its initial value and the pH value was in slightly acidic range (6.14 or 1.03 units lower than initial value). Taking into account the early phase of the experiment, it could be concluded that despite the closing of the system, the

Table 5. Water composition results without applied US and without additional CO_2 (closed system).

Time of experiment (min)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	alkalinity (ml HCl)	HCO_3^- (mg/L)
5.02	12.4	2.39	17.71	84.4	18.1	16.2	27.60	5.10	311.2
85.03	12.7	2.42	18.03	85.1	18.5	16.4	28.15	5.12	312.4
245.03	12.7	2.40	18.05	83.3	18.7	16.3	28.32	5.00	305.1
1235.02	12.5	2.37	17.73	83.4	18.3	16.0	27.90	5.00	305.1
1385.04	12.5	2.38	17.76	83.2	18.4	16.1	27.98	5.02	306.3

Table 6. Water composition results without applied US and with 570 mg of additional CO_2 (closed system).

Time of experiment (min)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	alkalinity (ml HCl)	HCO_3^- (mg/L)
0	12.2	2.27	17.53	83.7	19.6	17.1	30.40	5.03	306.9
256	12.5	2.40	17.85	83.5	n.a.	n.a.	n.a.	5.02	306.3
317	12.4	2.32	17.83	85.1	10.0	9.4	16.78	5.14	313.6
351	12.4	2.33	17.84	85.3	11.0	10.3	18.04	5.18	316.1
494	12.5	2.35	18.04	86.2	11.9	10.9	19.33	4.70	286.8
1394	12.4	2.69	17.79	84.9	12.7	11.4	20.03	4.80	292.9
1605	12.3	2.32	17.58	84.0	12.9	11.7	20.62	5.07	309.4

precipitation process (during heating) was not intensified significantly, because the operational temperature was too low.

The water composition results, presented in Tables 5 and 6, confirmed the above statements. They were made using ionic chromatography and automatic titration. The quantities of cations, such as Na^+, K^+, Mg^{2+}, Ca^{2+} and anions, such as Cl^-, NO_3^-, SO_4^{2-} were defined using ion chromatography. The automatic titration along with the incremental method was used to define the amount of hydrogen carbonate ions (HCO_3^-) and the alkalinity of the investigated water samples.

On the basis of the analyses of the corresponding calcium and magnesium contents it was find out that only slight variation in their quantities occurred during the experiments. These results were relevant for the preliminary hydro-chemical modelling, which showed that a slightly negative Langelier saturation index could be expected at such a process temperature.

Measurements were carried out over different seasons, in summer and winter, to study the seasonal influence on tap-water composition and to test the applied method's efficiency in various conditions. The tap-water composition used for the experiments was regularly analyzed in detail. The data in Table 7 represents the average values of the significant carbonate equilibria parameters regarding the drinking water used over the summer and winter periods.

Table 7. The average values of significant carbonate equilibria parameters regarding drinking water over summer (2006) and winter (2006/07) period in the Maribor area.

	Winter	Summer
Ca^{2+} ($mg \cdot L^{-1}$)	84..05	79.05
Mg^{2+} ($mg \cdot L^{-1}$)	17.62	15.26
HCO_3^- ($mg \cdot L^{-1}$)	309.05	284.16
pH	6.96	7.64

The measured values of all the parameters correlate to the existing data for ten-years' averages (Table 2), except that the values are generally higher than the averages, which could be related to the intensity of the rock weathering or shorter response time due to less precipitation. The calcium ions concentration was 10.3 % higher in winter 2007, and 45.4% higher in summer 2006 season compared to the ten-year (1995-2005) average. The water from the Maribor area also contains 12.2% more Mg^{2+} ions in summer and 15.1% more Mg^{2+} in winter season compared to the ten-year average.

5 CONCLUSION

The water quality optimization by introducing carbon dioxide is a very promising method in terms of reduction the costs of technological process and energy consumption. Another advantage of the described method is that it does not change the original water's mineralogical composition as it does not deplete the water of the minerals in comparison to the conventional methods, i.e. water softening. This should be taken into account especially when the preparation of the drinking water is an issue. The recently developed gas application is environmentally friendly. It does not produce any pollution or waste.

This completely adapted pilot plant with an advanced sensor system and an improved and more accurate gas-dosing system represents a useful technical tool for studying the behaviour of the described system operating under closed conditions with different tap-water compositions, and various seasonal influences.

The used tap water from the Drava basin aquifer in the summer of 2006 and the winter of 2007 generally contained larger quantities of dissolved minerals compared to ten-year averages. The concentrations of all the carbonate equilibria relevant contents correlate to the existing average values and their variations due seasonal influence, which means that the groundwater originating from the alluvial aquifer is richer in minerals in the winter and spring seasons, compared to the summer and autumn seasons.

The results were relevant for preliminary hydro-chemical modelling with a determination of saturation indexes, which confirm our presumptions and shows in most cases only a slightly negative Langelier saturation index ($-0.3 < LSI < -0.2$) at such an experimental temperature. The modelling will be continued and regularly updated with new data from experiments planned on the pilot plant at higher process temperature but without the online monitoring.

ACKNOWLEDGEMENTS

The presented research work is part of the project founded by the Waterpool Competence Network K-Net, Water Resources Management (WRM) and the Messer Company, Slovenia. The analytical part of the research work was also supported by an Ad Futura scholarship.

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Pre Announcement

Long Term Behaviour of Dams

LTBD09

2nd International Conference, 12th – 13th October 2009
Graz, Austria (Europe)

Jointly organized by

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Vienna University of Technology, Austria
University of Innsbruck, Austria
Hohai University, China
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Supported by

International Commision on Large Dams (ICOLD)
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The long-term behaviour of dams has gained more and more attention by dam engineers and geotechnical scientists. The second international conference on this topic will be held from October 12 to 13, 2009, in Graz (Austria) one of the recent European Capitals of Culture. The meeting will provide an excellent opportunity for engineers, scientists, and operators to present and exchange the experiences and latest developments related to the design, performance and rehabilitation of earth, rockfill and concrete dams including RCC and conventional concrete dams. Proposed sub-topics may include: methods of design and analysis of dams, experimental studies, dam monitoring and its instrumentation, long-term behaviour of construction materials for dams and their constitutive modelling, analytical and numerical investigations, seepage under saturated and unsaturated conditions, interaction of dam foundation and structure, seismic aspects and earthquake analysis, safety assessment, post–construction behaviour and dam maintenance, rehabilitation and dam heightening.

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