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# **RMZ – MATERIALS AND GEOENVIRONMENT**

PERIODICAL FOR MINING, METALLURGY AND GEOLOGY

## **RMZ – MATERIALI IN GEOOKOLJE**

REVIJA ZA RUDARSTVO, METALURGIJO IN GEOLOGIJO

### *Historical Review*

More than 90 years have passed since in 1919 the University Ljubljana in Slovenia was founded. Technical fields were joint in the School of Engineering that included the Geologic and Mining Division while the Metallurgy Division was established in 1939 only. Today the Departments of Geology, Mining and Geotechnology, Materials and Metallurgy are part of the Faculty of Natural Sciences and Engineering, University of Ljubljana.

Before War II the members of the Mining Section together with the Association of Yugoslav Mining and Metallurgy Engineers began to publish the summaries of their research and studies in their technical periodical *Rudarski zbornik* (Mining Proceedings). Three volumes of *Rudarski zbornik* (1937, 1938 and 1939) were published. The War interrupted the publication and not until 1952 the first number of the new journal *Rudarsko-metalurški zbornik - RMZ* (Mining and Metallurgy Quarterly) has been published by the Division of Mining and Metallurgy, University of Ljubljana. Later the journal has been regularly published quarterly by the Departments of Geology, Mining and Geotechnology, Materials and Metallurgy, and the Institute for Mining, Geotechnology and Environment.

On the meeting of the Advisory and the Editorial Board on May 22<sup>nd</sup> 1998 *Rudarsko-metalurški zbornik* has been renamed into "RMZ - Materials and Geoenvironment (RMZ -Materiali in Geokolje)" or shortly RMZ - M&G.

RMZ - M&G is managed by an international advisory and editorial board and is exchanged with other world-known periodicals. All the papers are reviewed by the corresponding professionals and experts.

RMZ - M&G is the only scientific and professional periodical in Slovenia, which is published in the same form nearly 50 years. It incorporates the scientific and professional topics in geology, mining, and geotechnology, in materials and in metallurgy.

The wide range of topics inside the geosciences are welcome to be published in the RMZ -Materials and Geoenvironment. Research results in geology, hydrogeology, mining, geotechnology, materials, metallurgy, natural and antropogenic pollution of environment, biogeochemistry are proposed fields of work which the journal will handle. RMZ - M&G is co-issued and co-financed by the Faculty of Natural Sciences and Engineering Ljubljana, and the Institute for Mining, Geotechnology and Environment Ljubljana. In addition it is financially supported also by the Ministry of Higher Education, Science and Technology of Republic of Slovenia.

Editor in chief

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## Calculation of stress-strain dependence from tensile tests at high temperatures using final shapes of specimen's contours

### Določitev odvisnosti napetost – deformacija z nateznimi preizkusi v vročem in na osnovi končnih oblik nateznih palic

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**Abstract:** The new mathematical model is proposed that enable calculation of true stress – true strain dependence from the results of tensile tests also after appearing of necking. Based on this model the computer program was developed which from the measured final shapes of the tensile specimens and from tensile testing data automatically determine the time evolution of the specimen's contour, strain rate and stress-strain relation. In order to tests and validate the model tensile tests at different prescribed strain rates and temperatures on specimens made of nickel alloy Alloy201 were carried out on thermo-mechanical simulator Gleeble 1500D. It was found that after occurrence of neck the true strain rate is constantly increasing throughout the test. Further it was found that plastic part of the rod can be well approximated with constant and with catenary but Bridgman correction can be determined only if catenary is used. Comparison of predicted evolution of minimal radius at the neck with measured one showed excellent agreement.

**Izveček:** V delu je opisan nov matematični model, s katerim je mogoče na podlagi rezultatov nateznih preizkusov tudi po pojavu skrčka določiti odvisnost prava napetost – prava deformacija. Na osnovi modela je bil narejen računalniški program, ki na podlagi izmerjenih končnih oblik

nateznih palic in podatkov nateznih preizkusov avtomatično določi časovni razvoj kontur nateznih vzorcev in izračuna hitrost deformacije ter zvezo med napetostjo in deformacijo. Model je bil preizkušen in preverjen z nateznimi preizkusi, ki so bili za nikljevo zlitino Alloy201 pri različnih predpisanih konstantnih hitrostih deformacije in konstantnih temperaturah narejeni na simulatorju termomehanskih metalurških stanj Gleeble 1500D. Ugotovljeno je bilo, da prava hitrost deformacije po pojavu skračka začne naraščati in narašča vse do konca preizkusa. Nadalje je pokazano, da lahko del palice, ki je v plastičnem stanju, zelo dobro aproksimiramo tako s konstanto kot tudi z verižnico, vendar pa je Bridgmanov popravek mogoče določiti le pri aproksimaciji z verižnico. Rezultati razvoja minimalnega radija v skrčku, dobljeni s predlaganim modelom, se odlično ujemajo z meritvami.

**Key words:** tensile test, necking, hot deformation, strain-stress curves.

**Ključne besede:** natezni preizkus, skrček, deformacija v vročem, krivulje deformacija – napetost

## INTRODUCTION

From the test for determination of hot workability of metallic materials it is required to enable measurement of force applied on sample as a function of its deformation at constant strain rate and constant temperature. There are three most important tests, i.e. compression test, torsion test and tensile test. Each of the tests has its own problems, i.e. weaknesses, which impeded gaining of reliable data about stress, strain, strain rate, deformability, etc. Compression test has seemingly the most advantages: geometry of cylindrical specimens is easy for machining and higher strains as well as strain rates can be achieved in comparison to tensile test, but due to the presence

of friction between compression anvil and specimen buckling can occur especially at slightly higher strains. Thus uniaxial stress state in deformed specimen is present only up to the beginning of its buckling when also reliable value related to hot deformation can be obtained. In case of exceeding of mentioned compression strain additional software is needed for gaining of more reliable data. Hot torsion testing takes place without presence of friction; moreover this test is very appropriate for assessment of hot workability since higher strain can be achieved by this type of testing that increase the reliability. But its weakness is in control (maintenance) of constant temperature during test, inhomogeneity of deformation so along working length of

specimen as well as in radial direction. Especially due to the latest weakness strain and strain rate can be expressed as equivalent strain and strain rate. At hot tensile testing also non-homogeneity of deformation occurs on specimen working length that is expressed by its necking. It is well known, that for tensile test homogenous deformation takes place only until appearance of necking which occurs at strains of approximately between 0.2 and 0.3, depending on precision of manufacturing of the tensile samples, on materials inhomogeneity, on temperature gradient along the tensile axis, etc.

When the neck appears, the stress state change from uniaxial to multi-axial must be taken into account. The correction due to multi-axiality is usually done by Bridgman correction, which presumes that portion of the contour inclose neighborhood of the minimal cross-section of the neck may be characterized by a single parameter, the radius of curvature of the circle osculating the profile at the neck.<sup>[1]</sup> But obtaining reliable data on stress – strain relation from tensile tests after appearance of necking is very difficult

task especially if testing is conducted at elevated temperatures, which is exactly the case if one wants to study hot workability of metallic materials.

The aims of this study are therefore to evaluate the possibility of applicability of tensile test for determination of hot working properties of metallic materials also after the appearance of necking and to introduce appropriate model for calculation of stress-strain dependence from the final shapes of contours of tensile loaded specimens.

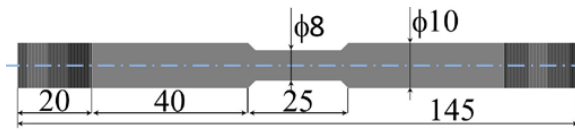
#### EXPERIMENTAL PROCEDURE

A commercially produced Ni alloy Alloy201 was supplied by Thyssen-Krupp GmbH as hot drowned rods with chemical composition given in Table 1 and equiaxed grain structure with an average grain size of about 16  $\mu\text{m}$ .

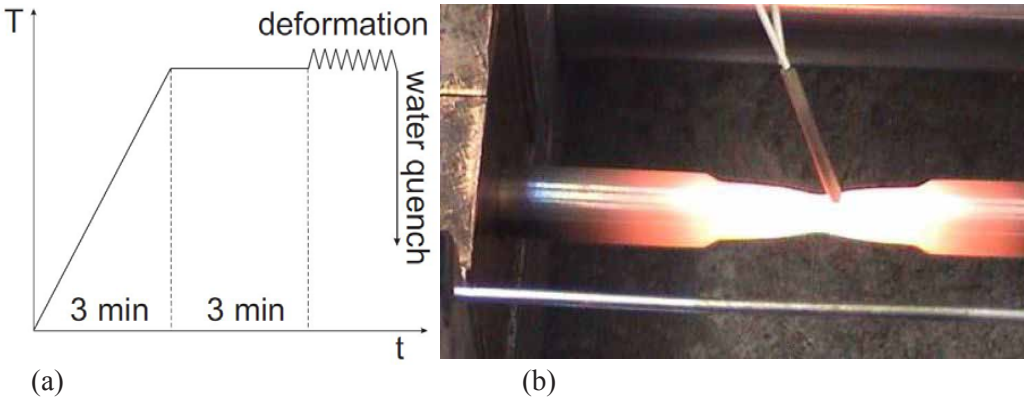
Cylindrical specimens with dimensions of 25 mm of effective length and of 8 mm in diameter where machined from supplied rods for hot tensile tests (see Figure 1 for specimen's geometry and dimensions).

**Table 1.** Chemical composition of the commercially pure Ni (Alloy201) tested in mass fractions  $w/\%$

<b>Mo</b>	<b>Cr</b>	<b>Si</b>	<b>S</b>	<b>Mg</b>	<b>Co</b>	<b>Cu</b>	<b>P</b>
0.001	0.004	0.05	0.001	0.03	0.07	0.006	0.006
<b>Mn</b>	<b>Ti</b>	<b>Fe</b>	<b>Sn</b>	<b>C</b>	<b>V</b>	<b>Al</b>	<b>Ni</b>
0.13	0.04	0.13	0.01	0.02	0.002	0.023	rest



**Figure1.** Dimension of specimen's for tensile testing.



**Figure2.** Schematic representation of temperature control (left), and shaping of contour (right) during hot tensile testing of Alloy201.

The hot tensile tests were carried out on Gleeble 1500D thermomechanical testing machine. The samples were deformed between 8 mm and 11 mm at temperatures from 800 °C to 1000 °C under prescribed constant strain rates between  $10^{-3} \text{ s}^{-1}$  and  $10^{-1} \text{ s}^{-1}$  assuming that deformation was homogeneous on entire working length. The temperature as a function of time during tensile tests is shown on Figure 2a, and specimen during testing is shown on Figure 2b.

#### DESCRIPTION OF THE MATHEMATICAL APPROACH

#### Model for description of contour of tensile specimen

Essentially the deformed shape-of-the-rod after tensile testing represents the history of traveling of the cross-section that separates the elastic and plastic state of material.<sup>[3, 4]</sup> The portion of material that in a given moment left the plastic state preserves its shape until the end of the experiment. Based on this fact, in what follows, the new model for description of evolution of specimen's contours during tensile testing will be introduced.

A cylindrical rod of radius,  $r$ , maintains its rotational symmetry around the longitudinal axis,  $z$ , during a tensile test, and thus its shape at given time,  $t$ , is determined by the rotational curve  $r = r(z, t)$ , which forms its sur-



face after rotation around longitudinal axis,  $z$ , of the rod. Before the test this curve is a cylinder  $r(z, 0) = r_0$ , where  $r_0$  is the initial radius of the rod. After the test is finished this curve must be carefully measured to obtain results in the form

$$r = r(z, t_k) \tag{1}$$

where  $t_k$  is the duration of the experiment. Initial volume of the rod of length,  $l_0$ , is  $V_0 = \pi r_0^2 l_0$ . The volume is conserved during plastic deformation, and thus volume for an arbitrary time can be expressed as

$$V(t) = V_0 = \pi \int_0^{l(t)} r^2(z, t) dz \tag{2}$$

where  $l(t)$  is the length of the rod at time  $t$ . By comparison between final shape of the rod and its shape at arbitrary moment after occurrence of neck, but before the end of the test, we ascertain that both shapes differ only in the middle, but the end parts are the same. Namely, the rod at the intermediate time is shorter and it has a smaller neck. Thus, we can conclude that the parts of the rod, which have the same shape as it is at the end of the test, were at that moment in an elastic state and the part, which is different, was in plastic state. Consequently, on deformed rod there are always two points that at given moment separate the plastic and

elastic parts of the rod. These two points were moving along the curve  $r = r(z, t_k)$ , during tensile test. Thus, the rod may be at any time divided into three parts

$$V_0 = \pi \left( \int_0^{l_l(t)} r^2(z, t) dz + \int_{l_l(t)}^{l_d(t)} r^2(z, t) dz + \int_{l_d(t)}^{l(t)} r^2(z, t) dz \right) \tag{3}$$

The first and last sections belong to the elastic part and the middle section to the plastic part of the rod. The final shape of the rod represents the line of movements of the points which separate plastic and elastic state of the material. The portion of the curve  $r = r(z, t_k)$ , that lies left of the minimal cross-section is a monotonically decreasing function and the portion on the right is a monotonically increasing function. Thus for the prescribed value of  $l_l(t)$  the value of  $l_d(t)$  can be calculated from the condition

$$r(l_l(t), t_k) = r(l_d(t), t_k) \tag{4}$$

From those two values the volume which is at given time in plastic state can be calculated

$$V_p = \pi \int_{l_l(t)}^{l_d(t)} r^2(z, t) dz \tag{5}$$

The idea for reconstruction of the intermediate shapes of the rod is now to find the approximate function  $f(z, t) \approx r(z, t)$ , for which

$$f(l_l(t), t) = f(l_c(t), t) = r(l_l(t), t_k) \quad (6)$$

where  $l_c(t)$  is the length from the beginning of the rod to the end of the plastic part. Since the contour of deformed rod is smooth, it immediately follows for the left end side

$$\left. \frac{\partial f(z, t)}{\partial z} \right|_{z=l_l(t)} = \left. \frac{\partial r(z, t_k)}{\partial z} \right|_{z=l_l(t)} \quad (7)$$

and for the right end one

$$\left. \frac{\partial f(z, t)}{\partial z} \right|_{z=l_c(t)} = \left. \frac{\partial r(z, t_k)}{\partial z} \right|_{z=l_d(t)} \quad (8)$$

Due to the constancy of the volume during plastic deformation, it also follows

$$V_p(t) = \pi \int_{l_l(t)}^{l_c(t)} f^2(z, t) dz \quad (9)$$

The value of  $l_c(t)$  which must be greater than the length of cylinder of the same volume and radius  $r = r(l_l, t_k)$  on one hand and must be smaller than  $l_d(t)$  on the other hand, is determined iteratively. For the function model that fulfils the conditions (6), (7), (8) and (9), the polynomial or any other suitable function could be used. In any case due to the mentioned conditions in every iteration

step the system of linear or non-linear equations must be solved depending on selected function. The simplest choice for the selection of function is certainly the constant, which upon rotation around its axes forms cylinder. Unfortunately the conditions (7) and (8) cannot be fulfilled for approximation with cylinder. Besides that, the radius of curvature of the contour at the minimal cross-section is needed for calculation of the Bridgman stress correction,<sup>[1]</sup> but for the approximation by cylinder this radius is infinite. On the other hand, for an arbitrary function this radius,  $R$ , can be calculated from

$$R = \left[ \left( \frac{\partial^2 f(z, t)}{\partial z^2} \right)^{-1} \left[ 1 + \left( \frac{\partial f(z, t)}{\partial z} \right)^2 \right]^{3/2} \right]_{z=z(r_{min})} \quad (10)$$

where  $r_{min}$  is the minimal radius at time  $t$ .

### Calculation of stress-strain dependence

After hot tensile testing the measurements of deformed rods were carried out by the measurement microscope, which automatically save the measured table of data  $r_i = r_i(z_i)$ . From measured data only those  $N$  points for which  $r_i \leq r_o$ , where  $r_o$  is radius of non-deformed rod, are taken into account. Additionally two points which are the nearest to the interval of  $N$  points are also con-

sidered. For reconstruction of contour the continuous function is needed and thus, cubic splines were applied for interpolation which yields continuous function  $r = r(z)$ . The next step is now the calculation of the volume of the rod which undergoes plastic deformation. Here the Simpson integration method<sup>[2]</sup> was employed for numerical integration of equation (2). In the present work two different functional models were chosen, namely catenary and constant. On deformed part of the rod  $K$  equidistant points separated for  $\Delta z$ , were selected and from that for the final length of deformed rod,  $l(t_k)$ , we find

$$l(t_k) = K\Delta z \tag{11}$$

After a number of trials we found that the value of  $\Delta z = 0.5$  mm is most suitable. In order to meet the condition (4), we find for each value of  $l_1 = i\Delta z$  corresponding value of  $l_d$  in every step  $i \in [1, K]$  by bisection. For those two values which are at that particular moment in elastic state we calculated volume of the rod,  $V_e$ , as

$$V_e = \pi \left( \int_0^{l_1} r^2(z, t) dz + \int_{l_d}^l r^2(z, t) dz \right) \tag{12}$$

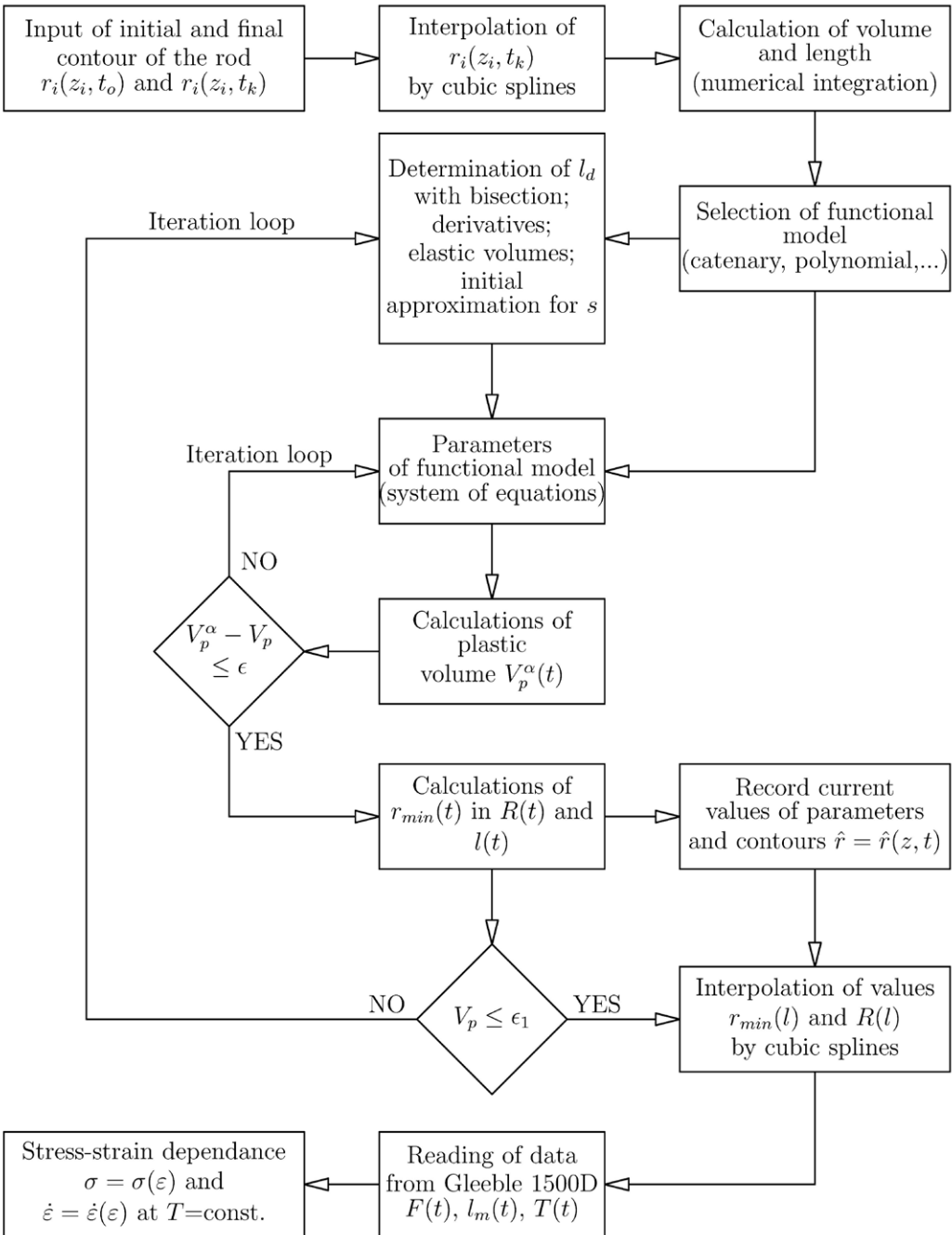
The above integrals (12) were also calculated by the Simpson's integration method. The volume of the part of the rod which is in plastic state the follow-

ing is true  $V_p = V_o - V_e$ . For the part of the rod which is in the plastic state two additional conditions are valid, namely it cannot be longer than  $s_1 V_p / \pi r^2(l_1)$  and cannot be shorter than  $s_2 = l_d - l_1$ , respectively.

Let construct the function

$$g(s) = V_p - \pi \int_0^s f^2(z, t) dz \tag{13}$$

which on the interval  $s_1 \leq s \leq s_2$  has the root, which is found by bisection. Further, the parameters of the functional model which fulfil the conditions (6)–(8) must be determined in every bisection step. We have the system of linear equations for the polynomial model (constant in the present work) and the system of non-linear equations for the catenary; where the last one is solved by the Newton method [2]. The iteration is interrupted when  $g(s) < \epsilon$ , where  $\epsilon$  is prescribed accuracy. First we determine  $r_{\min}$  and then from (10) the radius of curvature of the contour at the minimal cross-section,  $R$ . Both of them are combined into the vector. Described procedure is iterated until  $V_p > \epsilon$  or  $l_1 + l_d + s < l(t_k)$ . At that point we only need two continuous functions for  $r_{\min}(l)$  and  $R(l)$ . Again interpolation by cubic splines is employed. By means of  $r_{\min}^{(i)}$  and  $R^{(i)}$ , which are written as vectors, the second derivatives are calculated. Thus, the values of in-



**Figure 3.** Schematic of the algorithm that from measured final contours of deformed rods and from force-displacement data enables calculations of stress-strain dependence, time evolution of contours and strain rates.

terpolation function for any  $l$  are calculated. Finally, from the experimental results of the tensile test, which was conducted at constant temperature, the true stress is determined, that is further corrected by Bridgman formula[1]. Thus, we have

$$\sigma_{Br}(t_i) = \frac{F(t_i)}{\pi r_{min}^2(l(t_i))[1 + 2R(l(t_i)) / r_{min}(l(t_i))] \ln(1 + r_{min}(l(t_i))/2R(l(t_i)))} \quad (14)$$

and for the corresponding strain

$$\varepsilon_i = \ln(r_0/r_{min}(l(t_i))) \quad (15)$$

Since the dependence of strain on time is known, the dependence of strain rate on time during the test can be easily determined as

$$\dot{\varepsilon}_i = \frac{\varepsilon_{i+1} - \varepsilon_{i-1}}{t_{i+1} - t_{i-1}} \quad (16)$$

The computer program which takes as an input the final shape of the contour of tensile rod and data from tensile test, i.e. force and length of the rod as a function of time and which executes all the above described steps and enable determination of true stress – true strain curves and time evolution of true strain rate was written in programming language C++. The schematic of this program and algorithm is given on Figure 3.

## RESULTS AND DISCUSSION

### Technical curves and contour shapes of deformed rods

Tensile tests were carried out by uniaxial tension at prescribed displacements rates of anvils and at constant temperatures, where the tension force and displacement were continually recorded. After the test the contours for every deformed rod were carefully measured by microscope. The number of measured points on each section of the contour of deformed rod depended on its local curvature, but it always exceeded 100 points. Obtained technical curves for temperatures (800, 900, 1000) °C, and strain rates of (0.001, 0.01, and 0.1) s<sup>-1</sup> with corresponding final shapes of rods are shown in Figure 4.

After the transition of the material from elastic to plastic state the stress remains uniaxial, but the strain is three-axial; namely the elongation is uniform at uniformly decreasing of diameter. Uni-axiality of the stress is preserved until the occurrence of the neck. During the test the measured force is initially increasing until it reaches the maximum, and afterwards decreasing up to the end of the test. The amount of strain where the force is at maximum depends on material and on constitutive relation  $\sigma = \sigma(\varepsilon, \dot{\varepsilon}, T, \dots)$  as well as on changing of cross-section of specimen. Technical curve reaches the maximum when  $dF/dl = 0$ , where  $F$  stands

for force and  $l$  is elongation. From  $F = \sigma S$ , it follows that

$$\begin{aligned} \frac{dF}{dl} &= \frac{dF}{d\varepsilon} \frac{d\varepsilon}{dl} = \frac{1}{l} \left( S \frac{d\sigma}{d\varepsilon} + \sigma \frac{dS}{d\varepsilon} \right) \\ &= \frac{S}{l} \left( \frac{d\sigma}{d\varepsilon} - \sigma \right) \end{aligned} \quad (17)$$

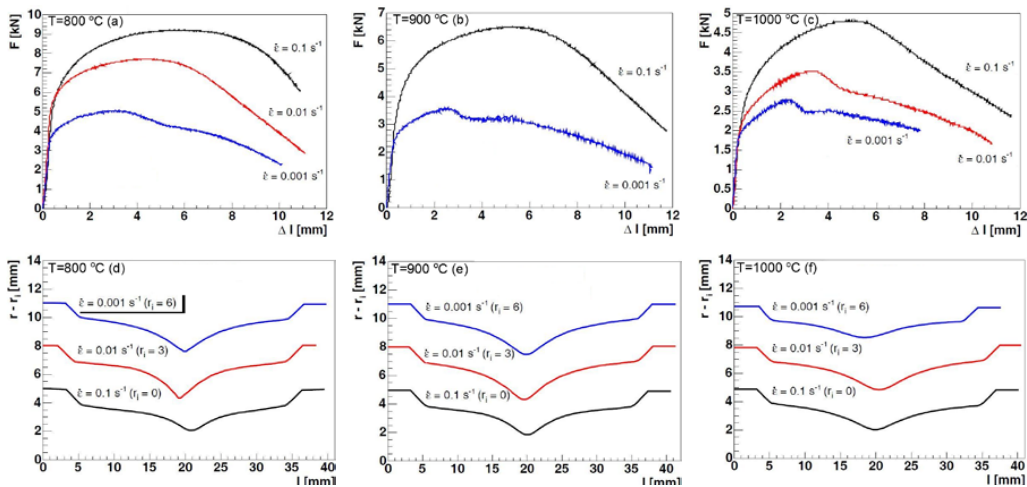
where the constancy of the volume has been taken into account. Therefore the force is maximal when  $d\sigma/d\varepsilon = \sigma$ .

### Formation of contours during straining

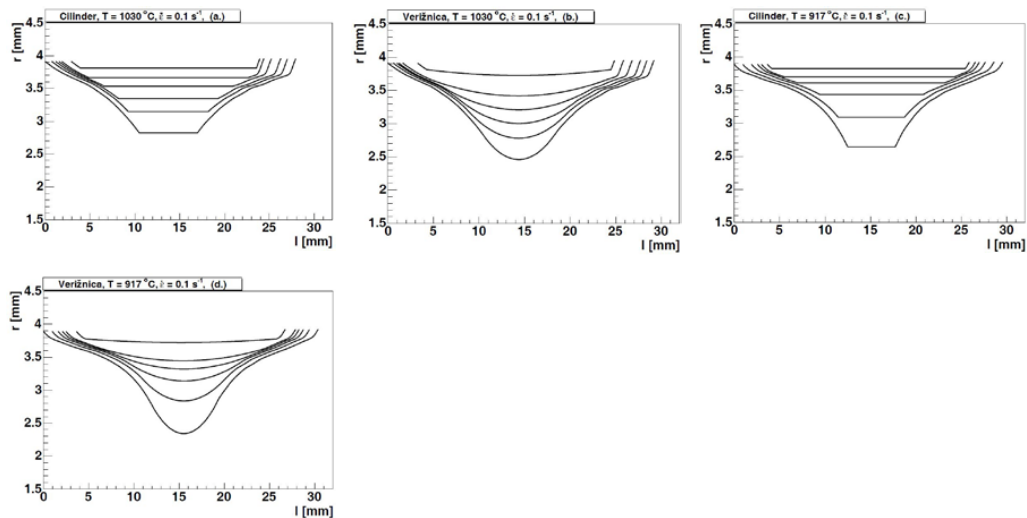
The key parameters that for the selected functional model determine how accurate the shape of contour can be determined are the volume  $V_0$ , which undergo plastic deformation, and the local slopes of the final contour. Of course, the last condition is not valid for the simplest i.e. cylindrical model, since the boundary conditions (7) and (8) cannot be fulfilled. Consequently, the shapes of contours calculated by cylindrical model are unrealistic (see Figures 5a and c), but nevertheless, as it will be demonstrated later, this model gives surprisingly good prediction of the evolution of the minimal radius of the rod within the neck during entire tensile test.

As we mentioned earlier the volume,  $V_0$ , is obtained by integration of the final contour of the rod along the  $z$ -axis considering condition  $r(z) \leq r_0$ , where  $r_0$  is initial radius of the work-

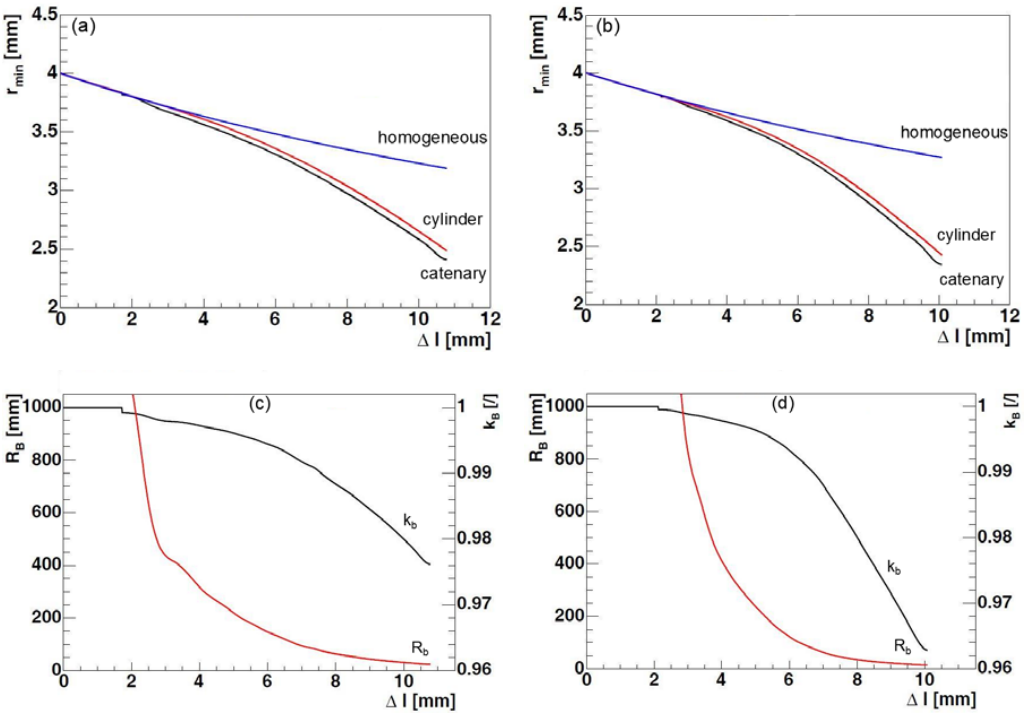
ing area of the rod. Since some plastic deformation occurs always also outside of the working area, this contributes to error. Namely, the slope of the contour at boundary between outside and inside area is very high. Therefore the calculated lengths of rods at initial steps of deformation are too long, and cross-sections are even smaller than those obtained at the end of deformation. Moving along the deformed contour results in shortening of calculated length as well as in increasing the minimal cross-section. According to the present model the length of the rod initially increases with strain, which is nonsense. To avoid this inconsistency the contour was calculated with our model only after the calculated length begins to increase with strain, before that the contour was calculated assuming homogeneous deformation. The examples of calculation of the rod shapes evolution during deformation for cylinder and for catenary at temperatures 1000 °C and 900 °C, and prescribed strain rate of 0.1 s<sup>-1</sup> are shown on Figure 5. If one wants to calculate the dependence of true stress on strain, the minimal cross-section, which is obtained from reconstruction of contour of the rod, must be given for every strain. The dependence of minimal radius on elongation for two temperatures calculated by catenary model is given on Figures 6a and 6b.



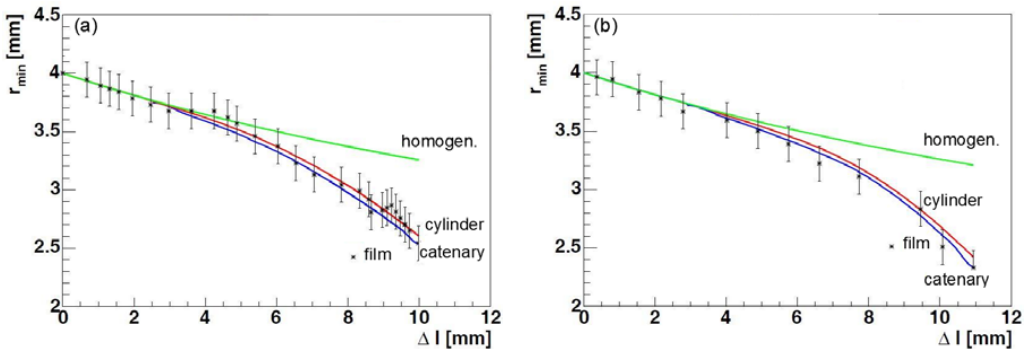
**Figure 4.** Technical curves force-elongation obtained with tensile tests for strain rates of (0.001, 0.01 and 0.1) s<sup>-1</sup> at temperatures of 800 °C (a), 900 °C (b), and 1000 °C (c) together with corresponding measured final shapes of deformed rods (d)–(f).



**Figure 5.** The calculated shapes of tensile rods for various stages of deformations at temperature of 1000 °C and strain rate of 0.1 s<sup>-1</sup> for cylindrical (a) and for catenary model (b). Calculation for cylindrical (c) and catenary (d) models at  $T = 900$  °C and strain rate of 0.1 s<sup>-1</sup>.



**Figure 6.** Comparison of dependence of minimal radius of deformed rod on elongation calculated by models for catenary, cylinder, and for assumption of homogeneous deformation for  $\dot{\epsilon} = 0.1 \text{ s}^{-1}$  at  $T = 1000$  °C (a), and  $T = 900$  °C (b). Evolution of the radius of the circle osculating the profile at the neck,  $R_B$ , and corresponding dependence of Bridgman correction coefficient,  $k_B$ , on elongation calculated by catenary model at  $T = 1000$  °C (c), and  $T = 900$  °C (d).



**Figure 7.** Comparison of dependence of minimal radii on elongation between measurements conducted by digital camera and calculated by studied models (catenary, cylinder, homogeneous deformation) for  $\dot{\epsilon} = 0.1 \text{ s}^{-1}$  at  $T = 950$  °C (a), and at  $T = 900$  °C (b).



For comparison the minimal radii calculated by cylindrical model and by assumption of homogeneous deformation are also given. It can be seen that the radius obtained by cylindrical model is very close to one obtained by catenary, whereas as expected the radius according to homogeneous deformation model after occurrence of necking start do deviate from values predicted by our models. Deformation is homogeneous approximately up to elongation of 2 mm that corresponds to strain  $\approx 0.2$ . As it was already mentioned, the transition from homogeneous to nonhomogeneous deformation leads to transition of uniaxial to three-axial stress state. For calculation of Bridgman correction,  $k_B$ , the radius of the circle osculating the profile at the neck,  $R_B$ , is needed. The  $R_B$  is calculated by equation (10) from reconstructed contours. The evolution of  $R_B$  and  $k_B$  are given on Figure 6c, and 6d, respectively. When the contours are calculated by the homogeneous deformation model, we set  $k_B \equiv 1$ , consequently the dependence of  $k_B(\Delta l)$  is discontinued at transition between both areas, with negligible error.

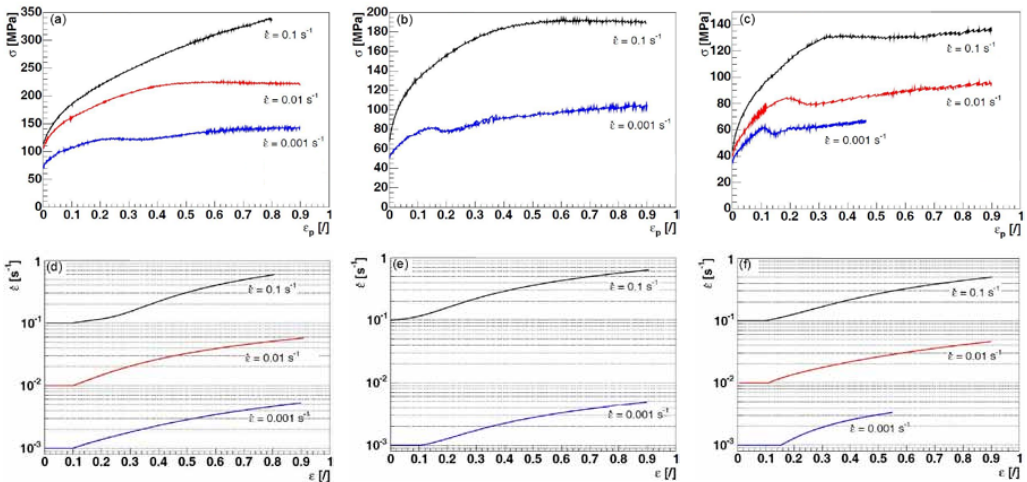
Calculated values of the time evolution of the minimal radius of the tensile specimens were compared with the values obtained from analysis of the pictures which were recorded by a digital camera, and we obtained reasonable agreement. These results are shown on Figure 7, were the maximal

estimated errors for minimal radius measured with camera are denoted. Due to intensive radiation from hot samples, the sharp boundary between the rod and surrounding was indistinct, thus the determination of real minimal radius was hindered.

### True stress–true strain curves

From technical force-elongation curves the true stress–true strain curves were determined by employing all the procedures explained in previous sections. They are shown on Figures 8a–c, whereas Figures 8d–e show the actual variation of strain rates during the tests.

For higher temperatures and/or lower strain rates the flow stress initially raises until a maximum is reached when hardening and softening are in balance. With increasing deformation, softening prevails over hardening and flow stress decreases. At strains  $\varepsilon > 0.2$  flow stress starts to increase and increases until the end of the experiment. This kind of behaviour in the later stages of deformation is a consequence of the continuously increasing strain rate after the appearance of necking. For the same reason flow curves for low temperatures and/or higher strain rates do not reach a maximum. Thus, we can conclude that after necking, the stress-strain curves are not flow curves as by definition flow curves are stress-strain curves at constant temperature and strain rate.



**Figure 8.** True stress-true strain curves, obtained by tensile tests for prescribed strain rates of (0.001, 0.01) s<sup>-1</sup>, and 0.1 s<sup>-1</sup> at temperatures of 800 °C (a), 900 °C (b), and 1000 °C (c) and corresponding variation of actual strain rate during the tests (d)–(f).

But in the future a series of carefully chosen testing conditions is planned with the aim to examine the possibility of finding the model that would describe the movements of jaws during the tests in such a way that constant true strain rate would be maintained during the entire test. Then it would be possible to determine flow curves with tensile testing to strains that are comparable with strains that can be obtained with compression testing.

## CONCLUSIONS

In this work a new mathematical model for calculation of true stress – true strain dependence from the results of tensile tests, which can be used also after appearing of necking, was pro-

posed. Furthermore the model was implemented into the computer program that enables determination of stress-strain curves from measurement of contours of deformed rods. The model and the computer program were validated by employing tensile tests for combinations of three different strain rates and temperatures on Gleeble 1500D testing machine for Ni alloy Al-201. The main findings can be summarized as follows:

1. It was found that, if the jaws of testing device are controlled in such a way that constant strain rate is obtained if homogeneous deformation is assumed, after appearance of necking the true strain rate is no longer constant, but it is increasing. Thus, stress-strain curves obtained in this way are not true flow

curves, as by definition flow curves are stress-strain curves at a constant strain rate.

2. In the present work two functions for description of evolution of the part of the contour which is in given moment in the plastic state, were tested, i.e. constant (approximation with cylinder) and catenary. Based on the comparison of the predicted evolution of contour and contours obtained by measurements with film camera it was found that both functions are capable of description of evolution of minimal radius of the rod in the neck with accuracy within the measurement error.
3. The main problem of applying the simplest function, i.e. the constant, is that it is not possible to determine the evolution of radius of curvature of the contour at the minimal cross-section and consequently Bridgman stress correction due to three-axiality of the stress cannot be applied since for constant this curvature is infinite. On the other hand using catenary this problem is avoided and true stress – true strain curves including Bridgman correction can be determined.
4. It could be possible to predetermine the movements of jaws during the tests in such a way that constant true strain rate would be maintained during the entire test or at least up to the true strains up to the value of 1.0, but this will require many more tests for different materials and at different thermo-mechanical conditions.

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## Petrochemical characteristics and geotechnical properties of crystalline rocks in the archean-proterozoic terrain of Ijero-Ekiti, southwestern Nigeria

### Petrokemijske značilnosti in geotehnične lastnosti kristaliničnih kamnin v arhajsko-proterozojskem kompleksu Ijero-Ekiti v jugozahodni Nigeriji

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**Abstract:** The Precambrian basement rocks around Ijero Ekiti, southwestern Nigeria were investigated with a view to elucidating its compositional features and geotechnical characteristics that may be related to industrial application. As part of the study approach, geological appraisal of the study area through systematic mapping was undertaken. Six samples each of the nine basement rocks were analysed for major elements using the Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) technique from Activation Laboratories, Ontario Canada and physical tests were conducted in Trevi Foundations, Lagos.

The systematic mapping of the study area revealed rocks comprising of the migmatite gneiss complex, quartzite, mafic-ultramafic assemblage and schistose rocks with paucity of granite and pegmatite forming steeply dipping intrusions into the older rock sequences. Petrographic examination indicates quartz, albite, biotite, hornblende, olivine, pyroxene and biotite as the common mineral constituents occurring in the basement rocks. Furthermore, from analytical result, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> accounts for a substantial percentage of the oxides in the rocks. However, calc gneiss has appreciably high CaO (15.15 %) and MgO (13.49 %) values. TiO<sub>2</sub> and P<sub>2</sub>O<sub>5</sub> are less than 0.1 % and 0.3 % respectively in all the rocks. Result of physical tests including specific gravity range between 2.54 g/cm<sup>3</sup> and 2.85 g/cm<sup>3</sup>;

compressive strength 32.4–84.50 N/mm<sup>2</sup>; wet density 2.01–2.30 g/cm<sup>3</sup>; water absorption capacity 0.02–0.24 %; porosity 0.01–0.58 % and pH 6.7–7.3. Industrial assessments using the evaluated physical properties indicate that the gneisses, quartzite, epidiorite and granite of the area are suitable for construction purposes.

**Izvleček:** Kamnine predkambrijske podlage z območja Ijero Ekiti v jugozahodni Nigeriji smo raziskali z namenom opredeliti njihovo sestavo in geotehnične lastnosti v luči njihove gospodarske uporabnosti. Del raziskave je obsegal sistematično geološko kartiranje študijskega ozemlja. Nadalje so bile v šestih vzorcih od vsake glavne kamnine podlage določene glavne kemične prvine z induktivno vezano plazemsko atomsko emisijsko spektrometrijo (ICP- AES) v Activation Laboratories v Ontariu v Kanadi, medtem ko so opravili fizikalne preiskave v laboratoriju organizacije Trevi Foundations v Lagosu v Nigeriji.

Geološko kartiranje območja je razkrilo kamnine kompleksa migmatitnega gnajsa, kvarcit, mafično-ultramafično združbo in skrilave kamnine z redkimi granitnimi in pegmatitnimi intruzijami, strmo vtisnjenimi v starejših kamninskih skladovnicah. S petrografsko raziskavo so bili ugotovljeni kremen, albit, biotit, rogovačo, olivin, piroksen in biotit kot poglavitni minerali v kamninah podlage. Analizni rezultati kažejo, da tvorijo glavni delež oksidov v kamninah SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>. Izjema je kalcitni gnajs, ki vsebuje visoke deleže CaO (15,15 %) in MgO (13,49 %). Vsebnosti TiO<sub>2</sub> in P<sub>2</sub>O<sub>5</sub> sta v vseh preiskovanih kamninah manjši od 0,1 % oziroma 0,3 %. Rezultati fizikalnih preizkusov so naslednji: prostorninska masa 2,54–2,85 g/cm<sup>3</sup>, tlačna trdnost 32,4–84,50 N/mm<sup>2</sup>, gostota v vlažnem stanju 2,01–2,30 g/cm<sup>3</sup>, vpojnost vode 0,02–0,24 %, poroznost 0,01–0,58 % in pH 6,7–7,3. Iz ugotovljenih fizikalnih lastnosti sledi, da so gnajsi, kvarcit, epidiorit in granit s tega območja primerni za uporabo v gradbeništvu.

**Key words:** Archean-proterozoic, geotechnical characteristics, basement rocks, compressive strength

**Ključne besede:** arhaik-proterozoik, geotehnične lastnosti, kamnine podlage, tlačna trdnost

## INTRODUCTION

Rugged relief characterized by prominent inselbergs is a common feature of many parts of Nigeria and in particular Ekiti State in the southwestern part of the country. These rocks, apart from not generating revenue from tourism, have not been fully exploited for other major economic purposes considering the available enormous quantity that occur in the area. Underutilization of these rocks may be attributable to insufficient geological information on the assessment of their properties on the one hand and shallow knowledge of what they could be used for on the other hand. These crystalline rocks could serve as raw material in most construction industries and as such contribute tremendously to the socio-economic development of the study area. This investigation is therefore aimed at evaluating the compositional features and physical characteristics of Ekiti crystalline rocks vis-à-vis their industrial application.

## REGIONAL GEOLOGICAL SETTING

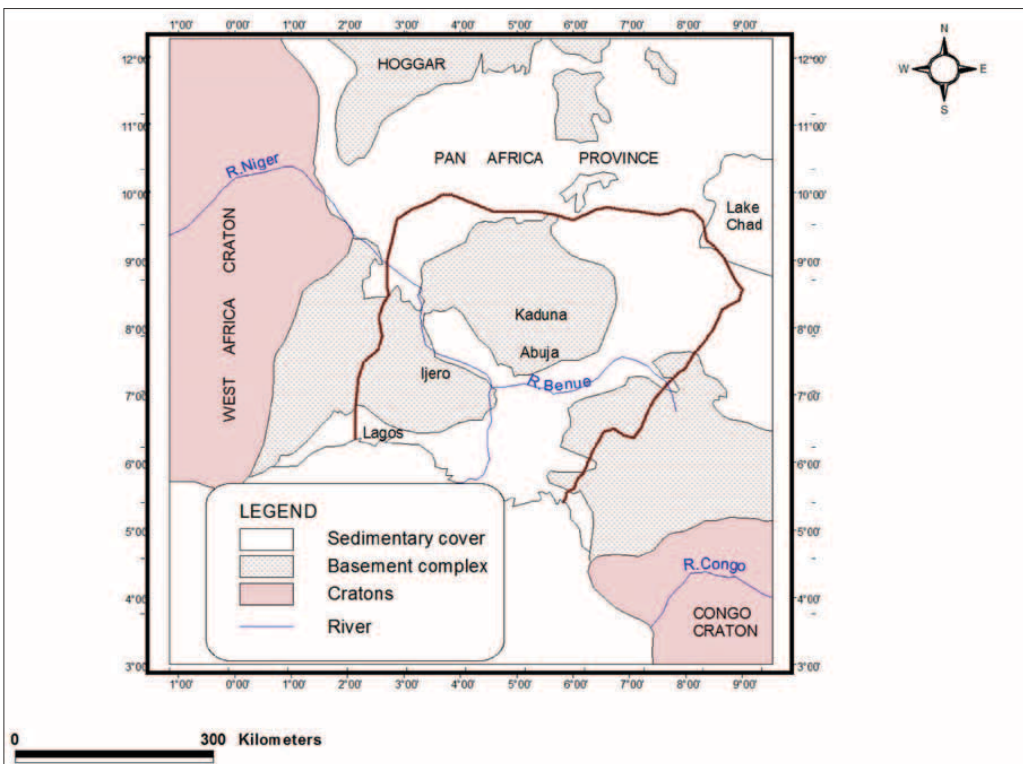
Nigeria lies within the Pan-African mobile belt specifically between the Congo craton to the southeast and West African craton to the west (Figure 1). Geology of Nigeria is made of sedimentary and crystalline rocks in almost equal proportions. The sedimentary rock sequences occupy the

marginal and intracontinental basins and belong to the Cretaceous-Recent age spectrum and lie unconformably on the basement complex rocks.

The rocks constituting the basement complex (Figure 2), despite disagreements on lithological delineations, are loosely categorized into three major groups: the migmatite-gneiss complex, the schist belts and the Pan-African Granites (ELUEZE, 2000). The migmatite gneiss complex 2.0–3.0 Ga; (RAHAMAN et al., 1988, DADA & BRIQUEU, 1998) is the oldest and most abundant rock type in the basement and is a product of several tectonothermal events that have brought rocks of various origins together. In addition, the schist belts, comprise low-grade metasediments and metabasic rocks that crop out in a series of distinctly N-S trending synformal troughs infolded into the crystalline migmatite-gneiss complex. They are about the best-studied group of rocks in Nigeria (RUSS, 1957, TRUSWELL & COPE, 1963) because of the mineralization such as gold, Banded Iron Formation (BIF), tin, tantalum, niobium and marble, associated with them (OYINLOYE, 2006). These rocks show distinctive petrological, structural and metallogenic features (OKUNLOLA, 2005). The schist belts in southwestern Nigeria include Iseyin-Oyan, Egbe-Isanlu, Ife-Ilesha and Igarra schist belts (RAHAMAN, 1976; ODEYEMI, 1977; ANNOR et al 1996). Others

are the Lokoja-Jakura, Toro-Gadabuiké belts (MUOTOH et al 1988, OKUNLOLA, 2001). The geochemistry of these rocks confirms their sedimentary nature but that of associated mafic and ultrabasic rocks has generated much controversy. The Older Granites display the most pervasive tectonic fabric symbolizing igneous reactivation attributable to the Pan-African events (OYAWOYE, 1964). The Older Granites in all cases include rocks of a wide range of compositions, structures and textures. The Older Granite is typically a fine-medium grained to coarse porphyritic rock

whose composition range from tonalite through granodiorite to granite and syenite. The lithological framework, deformation and metamorphism of the basement rocks are established in the works of MCCURRY (1976), AJIBADE (1976, 1980), ODEYEMI (1988), RAHAMAN (1976, 1988), EGBUNIWE (1982) and ELUEZE (1981). The geology of Ijero-Ekiti area has been reported in literature as part of the basement complex of southwestern Nigeria by MCCURRY (1976), TUNER (1983), RAHAMAN et al, (1988). This area is an Archaean-Early Proterozoic terrain GRANT (1970).



**Figure 1.** Map showing Nigeria within the Pan-African province between Congo and West African cratons (AJIBADE et al, 1988)

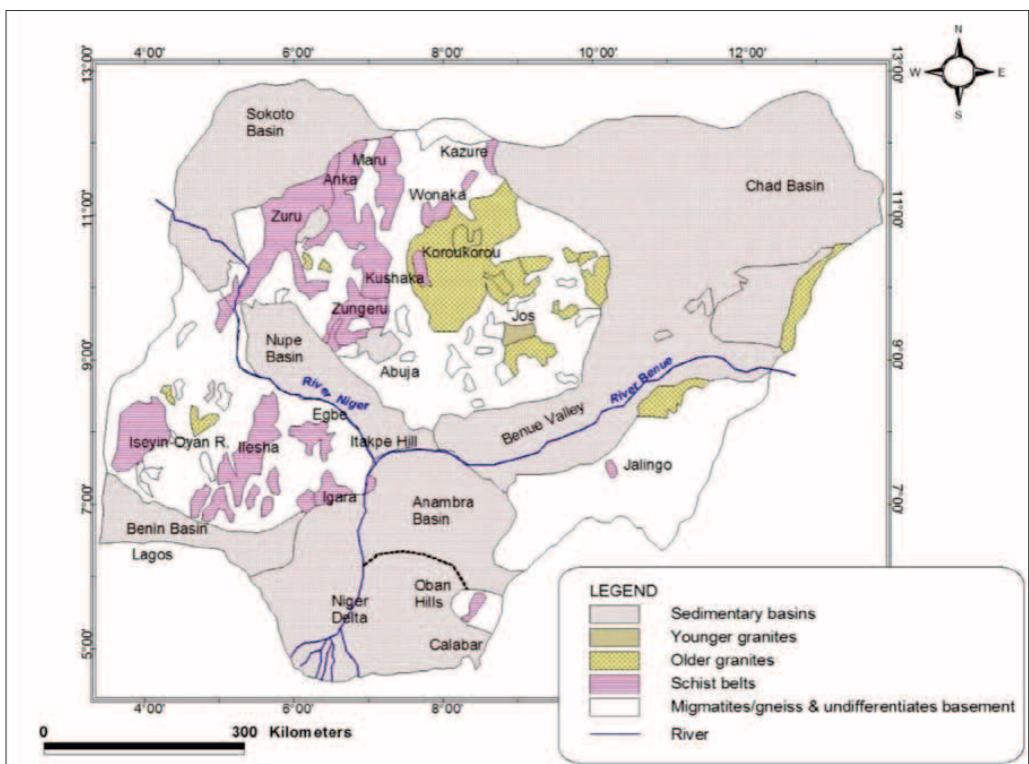


**LITHOLOGICAL RELATIONSHIP**

Geological appraisal through systematic mapping reveals that there are nine main lithologic units in Ijero area. They are: migmatite-gneiss, biotite-gneiss, calc-gneiss, quartzite, epidiorite, biotite schist, amphibole schist, granite, and pegmatite (Figure 3). Migmatite-gneiss occurs towards the eastern part covering about two-fifth of the study area. The rock exposures occur as highly denuded hills of essentially fine textures with closely spaced alternating bands of leucocratic and

melanocratic minerals. Outcrops of biotite-gneiss occur towards the west.

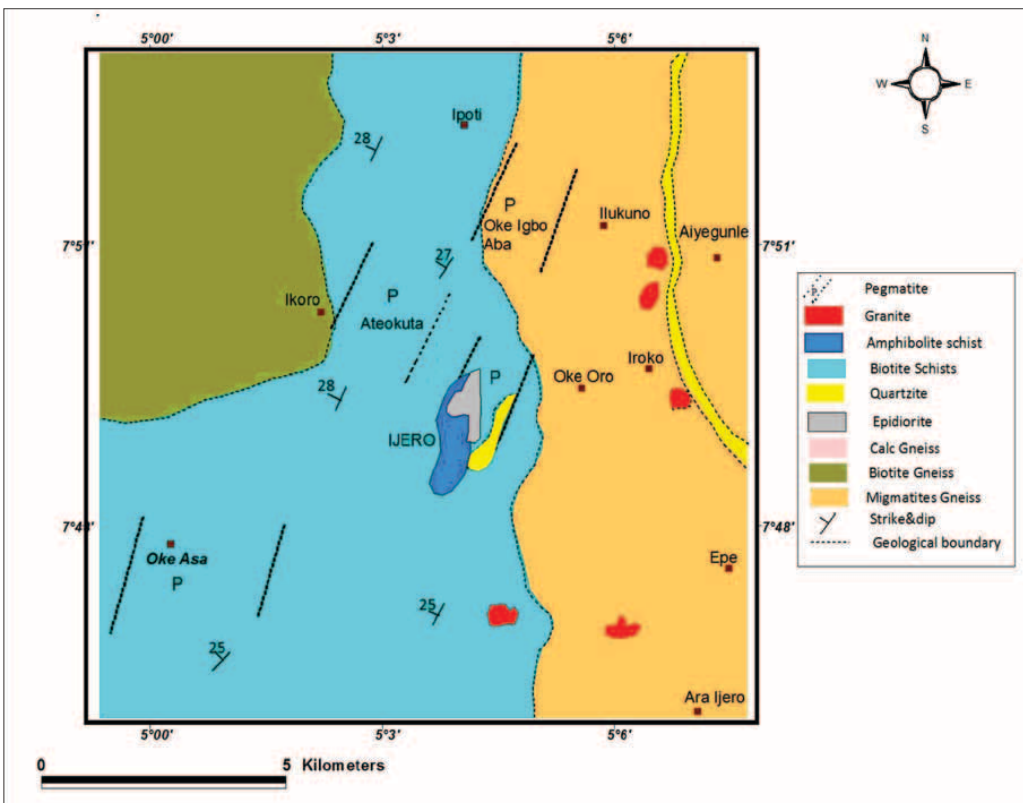
They are characteristically low lying, fine textured, and conspicuously foliated with abundance of platy biotite minerals sandwiched into zones that are markedly distinguishable from the light-coloured quartzo-feldspartic portions. In some areas, the foliations become so indistinct that the bands are lost leaving various indiscernible streaks of light and dark minerals. Calc-gneiss has grey to greenish colour with weakly developed foliations.



**Figure 2.** Generalized Geological Map of Nigeria showing the Basement Complex Rocks, Schist Belts, the Younger Granites and the Sedimentary Basins. (BLACK, 1980)

It is devoid of quartz vein intrusions and is restricted in occurrence only to a narrow strip in the eastern part of Ijero town. Quartzite occurs as ridge of steeply dipping, massively bedded, fine-medium grained bodies or an environment characterized by the abundance of quartz rubbles. Outcrops of epidiorite (a dense fine grained, dark coloured rock) are poorly exposed and are restricted to the southern part of the study area biotite schist and amphibole schist occurs toward the central part of the area and are bordered

in the west and east by biotite-gneiss and migmatite-gneiss respectively (Figure 3). They are highly susceptible to weathering and remarkably display a North-South foliation trend with poorly exposed outcrops occupying lowlands adjoining quartzite ridges, gneisses and granite pegmatites. Granite occurs as minor intrusive bodies while the pegmatite occur as distinct dykes of variable dimensions that is, veins and veinlets within the gneissic bodies with few cases of occurrence in batholithic masses.



**Figure 3.** Geological map of Ijero Ekiti area (OKUNLOLA & AKINOLA, 2010)

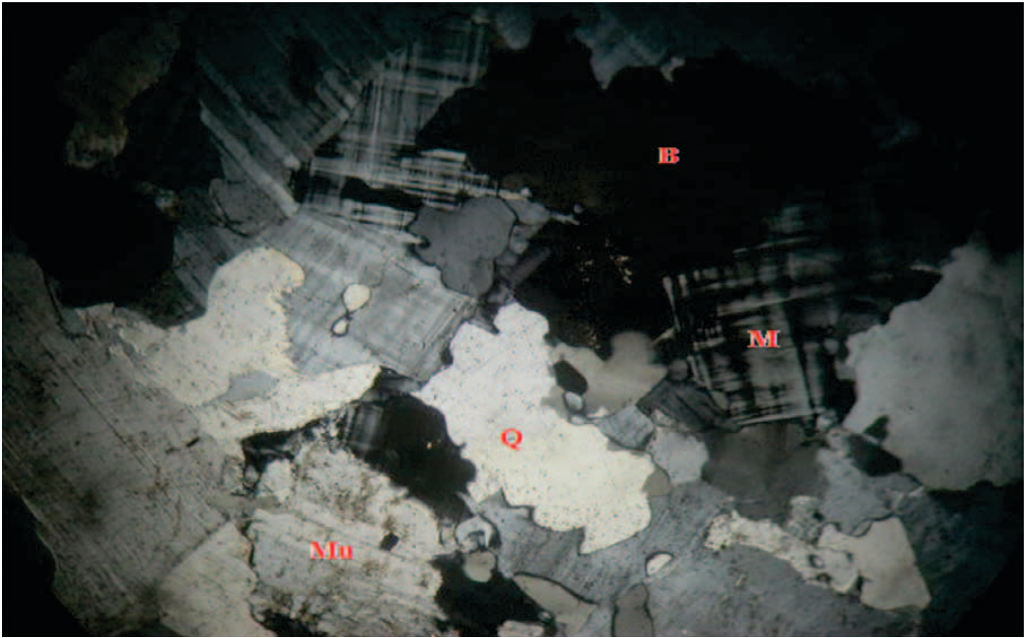
## MATERIALS AND METHODS

The study involves systematic geological mapping and samples were collected by standard geological techniques during which thin section study of each rock unit collected were undertaken. Caution was taken to ensure that the samples were fresh, unweathered and uncontaminated. Subsequently, for geochemical investigations, collected samples were dried at 60 °C, crushed, pulverized and sieved using sieve size 0.075 mm. 0.2 g samples aliquot was weighed into a graphite crucible and mixed with 1.5 g of  $\text{LiBO}_2/\text{LiB}_4\text{O}_7$ . The sample charged was heated in a muffle furnace for 30 min at 980 °C. The cooled bead was dissolved in 100 mL of 5 %  $\text{HNO}_3$  (ACS grade nitric acid) in de-mineralized water. An aliquot of the solution was poured into a propylene test tube. Calibration standard and verification standard were included in the samples sequence. Samples solution was aspirated into an ICP Mass Spectrometer (Perkin-Elmer Elan 9000) for the determination of the major oxides at the Activation Laboratories in Ontario Canada. In addition, physical test were carried out on the basement rocks to determine their industrial characterization. The tests conducted include specific gravity (SG), compressive strength (CS), wet density (WD), water absorption capacity (WAC) and porosity (P, %) following the American Society for Testing and Materials 1985, D2487-83

procedures while pH determinations were carried out using a multiparameter portable meter (model Testr-35). Bulk porosity determination is the measure of the quantity of water which a rock will absorb when immersed in water and is measured by, the difference between the dry weight of the sample and the weight after soaking expressed as percentage of the dry weight. Compressive strength is determined by statically loading a cylinder of rock to fracture, the load being applied across the upper and the lower faces of the sample.

## PETROGRAPHY

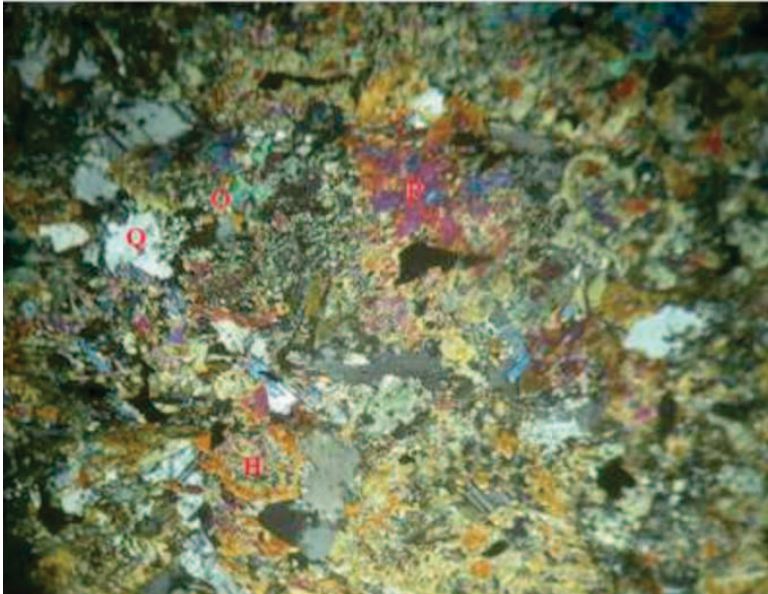
Petrographic examinations indicate that migmatite-gneiss contains feldspar, quartz, muscovite and biotite. The biotite content is low and mineral alignment is less pronounced. Other essential components include ferromagnesian minerals like hornblende. Quartz and feldspars alone constitute up to 70 % of the rock in thin section. Feldspar is second to quartz in abundance while ferromagnesian and opaque minerals such as garnet and magnetite constitute the coloured minerals (Figure 4). The mineral constituents of biotite gneiss are similar to those of the migmatite-gneiss except that they appeared stretched and elongated such that the longer axis appears in the same direction. A larger percentage of the biotite occurs in groundmass and mineral outlines are well defined.



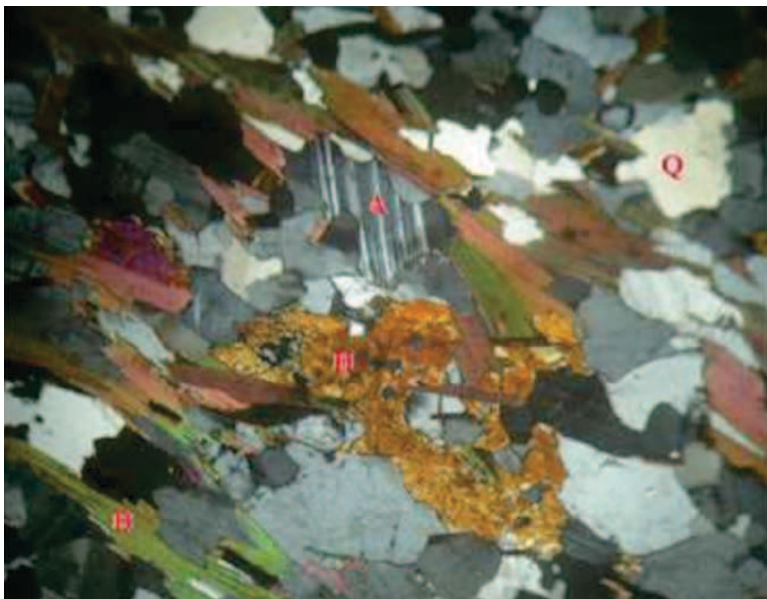
**Figure 4.** Photomicrograph of migmatite gneiss in transmitted light showing cross-hatched twinned microcline (M), large plates of biotite (B), fine grained quartz crystals (Q) and muscovite (Mu)

Calc-gneiss is mainly composed of calcite, quartz with muscovite. Most of the minerals show evidence of strain and are altered. Calcite, quartz and muscovite are the dominant minerals accounting for 90 % of the modal composition. Ferromagnesian minerals like olivine, pyroxene and hornblende dominate the modal composition of epidiorite (Figure 5). Quartz, muscovite, hornblende and accessory opaque minerals dominate the composition of biotite schist. Quartz occurs as small, colourless and sometimes cloudy xenomorphic crystals. Accessory zircon occurs as short idiomorphic crystals while the opaque minerals are few but existing as scat-

tered euhedral grains (Figure 6). Biotite occurs in dominant amounts and forms the major groundmass minerals. In quartzite, quartz occurs as granoblastic and unaltered euhedral crystals with well-defined outlines. It exhibits weak birefringence, low relief with wavy extinction. However, some of the quartz grains appear cloudy. Muscovite form supporting minerals as they occupy intergranular spaces of interlocking quartz crystals and sometimes occur as colourless elongated plates. In granite, the feldspars are large, well-formed crystals of albite while quartz occurs as irregular masses of colourless and unaltered grains.



**Figure 5.** Photomicrograph of fine grained epidiorite in transmitted light showing dominance of ferromagnesian minerals, olivine (O), Pyroxene (P), Quartz (Q) and Hornblende (H)



**Figure 6.** Photomicrograph of fine-grained biotite schist in transmitted light showing euhedral quartz (Q), albite (A), hornblende (H), and platy biotite (B).

In pegmatite, the feldspars exist as porphyries of microcline with its characteristic strong cross hatched twinning and strong to weak micro perthitic intergrowth. Tourmaline crystals exhibit long needle-like prismatic shapes with acicular habit (Figure 7).

Modal analysis (Table 1) shows that quartz is adequately represented in most of the basement rocks with quartzite, granite, gneisses and pegmatite showing larger percentages while epidiorite, amphibole schist and calc-gneiss record substantially low values. Plagioclase is well represented in granite, pegmatite and the gneisses but with low representation in the schistose rocks. Biotite is another mineral that cut across most of the basement rocks. However, highest percentages are recorded in biotite schist and biotite gneiss while calc-gneiss does not show any trace of the mineral at all. As regards amphibole schist, hornblende has the highest percentage while it is of an average value in epidiorite. Olivine and pyroxene are only represented in epidiorite while tourmaline and lepidolite are present only in pegmatite.

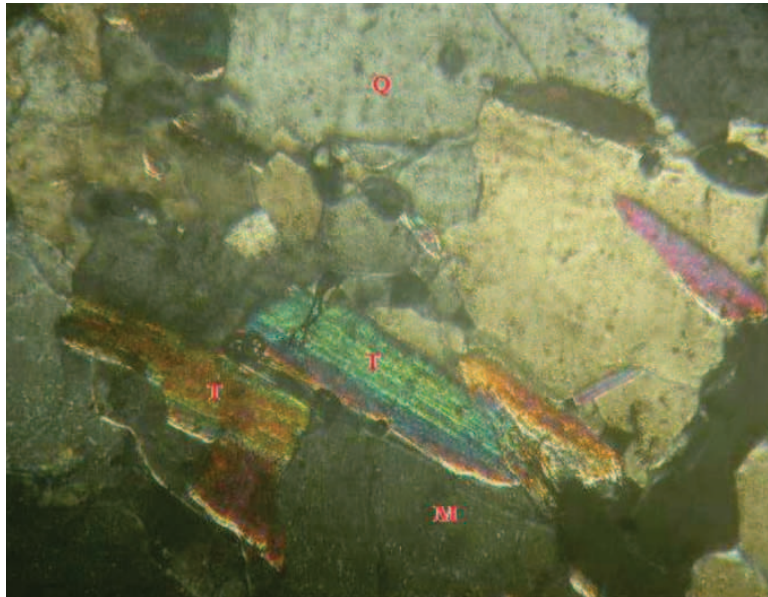
## RESULTS AND DISCUSSION

### Geochemical features

Geochemical result (Table 2) shows that average  $\text{SiO}_2$  content of all the basement rocks are high and range

from lowest value in epidiorite (55.72 %) to highest value in granite (73.61 %). The gneisses have average  $\text{SiO}_2$  similar to those found around Ilesha area (ELUEZE, 1981). Alumina content ranges from lowest in calc-gneiss (9.23 %) to higher values in amphibole schist (15.62 %) and highest in biotite schist (18.03 %). The mean  $\text{Al}_2\text{O}_3$  content of the schistose rock around Ijero is generally higher than similar rocks encountered around Ibadan (OKUNLOLA et al, 2009)

Mean  $\text{Fe}_2\text{O}_3$  content of Epidiorite (11.16 %) and biotite schist (8.53) are comparable. These values are higher than biotite gneiss (7.02 %) and pegmatite (6.49 %). Low mean MnO value is common to all the basement rocks except quartzite (2.18 %) which records the highest, and this value is higher than calc-gneiss (1.64 %). All other basement rocks have average MnO values that are less than 0.6 %, for instance, epidiorite and biotite schist both record 0.08 %. Mean MgO content of Calc-gneiss (13.49 %) is slightly lower than epidiorite (14.80 %). Other rocks, amphibole schist (6.25 %), biotite gneiss (3.08 %), biotite schist (8.94 %), quartzite (1.00 %) have low mean values while the remaining basement rocks record lower values. Average CaO values of migmatite gneiss (2.51 %), biotite gneiss (2.14 %) and amphibole schist (2.04 %) are comparable. However, these



**Figure 7.** Photomicrograph of pegmatite in transmitted light showing tourmaline crystals (T), Quartz (Q) and muscovite (M).

**Table 1.** Modal composition of the basement rocks in Ijero-Ekiti area (%)

Minerals	*MG	*BG	*CG	*QZ	*EP	*BS	*AS	*GR	**PG
Quartz	48	42	25	56	17	34	18	46	37
Plagioclase	22	18				4	10	35	12
Microcline							12		7
Calcite			36						
Muscovite			32	29	11				26
Biotite	23	32		10	13	58	15	5	8
Hornblende	4	6			18	4	32	6	1
Olivine					17				
Pyroxene					21			5	
Tourmaline									8
Epidote			6		4		3		
Lepidolite									4
Opaque	3	3		5	2		9	2	
Others							1	1	

MG (Migmatite gneiss), BG (Biotite gneiss), CG (Calc-gneiss), QZ (Quartzite), EP (Epidiorite), BS (Biotite schist), AS (Amphibole schist), GR (Granite), PG (Pegmatite); \* Average of 6 samples, \*\* Average of 5 samples

values are lower than quartzite (6.54 %), epidiorite (4.04 %), and calc-gneiss (15.15 %). Mean  $\text{Na}_2\text{O}$  value of migmatite gneiss (3.32 %) and biotite gneiss (3.00 %) are comparable. These values are higher than epidiorite (1.97 %) and pegmatite (2.38 %). While calc gneiss (1.08 %), quartzite (1.21 %) and amphibole schist (1.34 %) are within similar range. Average potash content of pegmatite (6.77 %) is higher than the comparable value for migmatite gneiss (4.18 %) and biotite schist (4.08 %) while lower mean values are recorded for biotite gneiss (3.86 %), quartzite (1.96 %) and amphibole schist (1.70 %). Other oxides,  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  do not follow any discernible pattern and their values are generally less than 0.5 % in all the basement rocks. Loss on Ignition values are generally low and fall between 1.07 % in pegmatite and 5.27 % in biotite schist.

### Physical and mechanical features

The result of the physical tests (Table 3) shows that amphibole schist has the lowest specific gravity value of  $2.54 \text{ g/cm}^3$  while biotite gneiss has the higher value of  $2.85 \text{ g/cm}^3$ . Compressive strength values fall within a wide range with amphibole schist having the least value ( $32.4 \text{ N/mm}^2$ ) and Granite the highest value ( $84.5 \text{ N/mm}^2$ ). Lowest wet density was obtained for amphibole schist ( $2.01 \text{ g/cm}^3$ ) and highest for migmatite gneiss ( $2.31 \text{ g/cm}^3$ ), Water Absorption

capacity values are generally low and quartzite records the lowest (0.04 %) while amphibole schist (0.28 %) records the highest. Biotite gneiss and quartzite record the lowest bulk porosity value of 0.01 % while the highest value (0.58 %) was in biotite schist. The pH values range generally between 6.7 and 7.4 with the least and highest value in migmatite gneiss/granite and biotite schist respectively.

### Industrial assessment

Physical tests on the basement rocks are to ascertain their usefulness as building materials. Building stones denote pieces of rock that may undergo cutting, sawing, shaping and sometimes polishing and still be useful for construction purpose. The main requirements for building stones are strength, durability, workability, and availability. To be useful for construction purpose, a minimum compressive strength of  $36 \text{ N/mm}^2$  ( $367.2 \text{ kg/cm}^2$ ) is required (ASTM, 1970). Many of the Basement rock including migmatite gneisses, biotite gneiss, calc gneiss, quartzite and granite meets the above specification (Table 3).

However, the schistose rocks have lower compressive strengths due to their fissility. Although, pegmatite meets the minimum strength requirement for use as building stone, its large-sized particles are a disadvantage. Migmatite and biotite gneiss are highly meta-



**Table 2.** Chemical composition of the Basement rocks of Ijero-Ekiti

Oxide in %	*MG	*BG	*CG	*QZ	*EP	*BS	*AS	*GR	**PG
SiO <sub>2</sub>	68.42	65.63	53.40	74.86	55.72	54.22	57.07	73.61	67.46
Al <sub>2</sub> O <sub>3</sub>	15.13	15.49	9.23	6.25	9.01	18.03	15.62	15.43	13.90
Fe <sub>2</sub> O <sub>3</sub>	3.47	4.02	2.77	3.04	11.16	8.53	9.83	2.37	6.49
MnO	0.25	0.21	1.64	2.18	0.08	0.08	0.56	0.10	0.42
MgO	0.33	3.08	13.49	1.00	14.80	8.94	6.25	0.08	0.03
CaO	2.51	2.14	15.15	6.54	4.04	0.15	2.04	0.96	1.11
Na <sub>2</sub> O	3.32	3.00	1.08	1.21	1.97	0.57	1.34	1.77	2.38
K <sub>2</sub> O	4.18	3.86	1.45	1.96	0.93	4.08	1.70	3.21	6.77
TiO <sub>2</sub>	0.08	0.07	0.09	0.03	0.06	0.03	0.05	0.03	0.01
P <sub>2</sub> O <sub>5</sub>	0.05	0.02	0.01	0.01	0.02	0.01	0.01	0.14	0.26
LOI	2.24	2.47	1.60	2.62	2.20	5.27	5.23	2.30	1.07
Total	99.98	99.99	99.91	99.70	99.99	100	99.70	100.00	99.83

MG (Migmatite gneiss), BG (Biotite gneiss), CG (Calc-gneiss), QZ (Quartzite), EP (Epidiorite), BS (Biotite schist), AS (Amphibole schist), GR (Granite), PG (Pegmatite); \* Average of 6 samples, \*\* Average of 5 samples

**Table 3.** Physical properties of the major basement rocks around Ijero-Ekiti

Rock name	SG/ g cm <sup>-3</sup>	CS/ (N/mm <sup>2</sup> )	WD/ (g/cm <sup>3</sup> )	WAC/ %	P/(%)	pH
Migmatite Gneiss	2.72	63.1	2.31	0.13	0.03	6.7
Biotite Gneiss	2.85	56.1	2.23	0.09	0.01	6.9
Calc-Gneiss	2.72	43.9	2.17	0.16	0.03	6.9
Quartzite	2.65	61.8	2.29	0.04	0.01	7.0
Epidiorite	2.75	72.0	2.24	0.10	0.03	7.3
Biotite Schist	2.69	35.3	2.01	0.24	0.58	7.4
Amphibole schist	2.54	32.4	2.04	0.28	0.41	7.1
Granite	2.70	84.5	2.11	0.02	0.02	6.7
Pegmatite	2.71	46.0	2.06	0.13	0.05	6.8

SG: Specific gravity, CS: Compressive strength, WD: Wet density, WAC: Water absorption capacity, P: Bulk porosity and pH: Acidity.

morphosed banded rocks that contains beautifully coloured alternating bands of light and dark colours. The outcrops of these rocks are particularly common around Ilukuno, Oke-Oro, Iroko and Ayegunle area and towards the southern

part of Ara-Ijero and Epe. These outcrops could serve as raw materials for building applications such as as gneiss is used to decorate the outside of buildings, making of floor tiles and counters, aggregate in concrete mixing etc.

A quarry site is located along Epe road where a gneissic outcrop serves as a source of stone aggregate for more than three decades. Local sources indicate that most of the roads in the area were built with products from this stone mill. The major quartzite ridge of the area has been quarried locally to produce materials for foundation works and cement mixing for concrete slabs.

## CONCLUSION

Ijero-Ekiti is within the Basement Complex terrain of southwestern Nigeria and underlain by gneisses, quartzite, epidiorite, schists, granite and pegmatite. The granite and pegmatite form steeply dipping intrusions into older rock sequences. Most of the basement rocks are rich in quartz, feldspars, biotite and hornblende. Calc-gneiss is enriched in calcite and epidiorite has high percentage of ferromagnesian minerals including hornblende, biotite, and pyroxene. The mineralogical variations also reflect in the chemical composition of the rocks for instance, calc gneiss has high percentage of CaO and MgO whereas the gneisses, quartzite, granite and pegmatite are highly siliceous. Physical properties of the basement rocks indicate that they possess average specific gravities, moderate wet densities, high compressive strengths, and low porosities. A slightly acidic to mildly basic pH characterizes the rocks

and they are comparable to similar rocks found elsewhere within the basement complex. Economic evaluation indicates that the gneisses, quartzite, epidiorite and the granite have compressive strength values within the limits required for use as foundation material and building stones.

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## The groundwater potential evaluation at industrial estate Ogbomoso, Southwestern Nigeria

### Ocena potenciala podtalnice na industrijskem območju Ogbomoso v jugozahodni Nigeriji

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**Abstract:** Vertical Electrical Sounding method was used to map Oyo State industrial estate Ogbomoso with a view to determining the groundwater potential of the study area. Ten Vertical Electrical Soundings (VES) were carried out across the area using the schlumberger electrode array configuration with current electrode separation (AB) varying from 130 m to 200 m. Nine out of the ten modeled curves were H-type where the remaining one was KH-type. The geoelectric sections obtained from the sounding curves revealed 3-layer and 4-layer earth models respectively. The models showed the subsurface layers categorized into the topsoil, weathered/clay, fractured layers and the fresh bedrock. The weathered basement and fractured basement are the aquifer types delineated for the area. Groundwater potential evaluated from the maps (i.e. overburden thickness, anisotropic coefficient, weathered layer isothickness, weathered layer isoresistivity, transverse resistance and bedrock relief maps) revealed that the Southern and Eastern parts of the study area are the most promising region for borehole development. However, North-eastern region of the study area can also be considered as fair for borehole development.

**Izvleček:** Z metodo vertikalnega električnega sondiranja so kartirali industrijsko območje države Oyo Ogmoboso v Nigeriji z namenom opredeliti potencial podtalnice. Opravili so sedem vertikalnih električnih sondiranj (VES) s Schlumbergerjevo razporeditvijo elektrod in razdaljami med tokovnima elektrodama (AB) od 130 m do 200 m. Devet izmed desetih modeliranih krivulj je bilo vrste H, preostala pa vrste KH. Geoelektrični profili, izdelani po krivuljah sondiranja, razkrivajo triplastne in štiriplastne modele. Zastopane so plasti vrhnjega nivoja tal, preperine/gline, razpokane kamnine in nepreperene kamnine. Vodonosnika na preiskovanem ozemlju sta v prepereli podlagi in razpokani podlagi. Potencial podzemne vode, ocenjen po izdelanih kartah (debeline pokrova, koeficienta anizotropnosti, navidezne debeline in navidezne upornosti in reliefa preperinske plasti), kaže, da so najperspektivnejši za vrtanje južni in vzhodni deli raziskovanega območja. Potencial vode v severovzhodnem delu je ocenjen kot povprečen.

**Key words:** vertical electrical sounding, groundwater potential, fractured basement, thick overburden, aquifer, industrial estate

**Ključne besede:** vertikalno električno sondiranje, potencial podtalnice, razpokana podlaga, debel pokrov, vodonosnik, industrijska lokacija

## INTRODUCTION

The importance of groundwater as a supply source to the socio-economic development of a country is tremendous. Though, the state water corporations make use of some minor rivers as a means of water supply to the populace especially in the urban areas but this water is insufficient for domestic uses let alone its availability for industrial uses. Constant supply of water cannot be denied in any indus-

trial settings, as it serves as one of the amenities to be available in industries. Therefore, groundwater has proved itself to be the only available source of water for industrial uses.

The use of geophysics for both groundwater resource mapping and for water quality evaluations has increased dramatically over the years. The Vertical Electrical Soundings (VES) has proved very popular with groundwater studies due to simplicity of the technique.

Groundwater has become immensely important for human water supply in urban and rural areas in developed and developing nations alike (OMOSUYI, 2010). Using this method, depth and thickness of various subsurface layers and their water yielding capabilities can be inferred. Therefore, evaluation of groundwater potential at industrial estate Ogbomoso was done in order to know the groundwater yielding capabilities or groundwater conditions of the study area. In basement complex, unweathered basement rocks contain negligible groundwater. Significant aquifers however, develop within the weathered overburden and fractured bedrock. This research is particular to know feasibility of potable water borehole in the industrial estate (i.e. to know the promising areas for groundwater prospects within the study area). This was done in order to advise the building engineers and the users of the estate not to build factories, warehouses or administrative buildings on the available zones for groundwater exploration and to know the promising zones for groundwater exploration in the study area. However, the groundwater conditions of industrial estate when properly understood could be used as an effective tool in the planning of reliable water borehole in the study area.

The study area is underlain by Precambrian rocks of the Nigerian Basement

Complex where aquifers are both isolated and compartmentalized. These rocks in their deformed state possess little or no primary intergranular porosity and permeability and thus the occurrence of groundwater is due largely to the development of secondary porosity and permeability by weathering and/or fracturing of the parent rocks (ACWORTH, 1987; OLORUNFEMI & FASUYI, 1993; OLAYINKA et al, 1997). Groundwater localization in this region is controlled by a number of factors which include the parent rock type, the depth, extent and pattern of weathering, thickness of weathered materials, and the degree, frequency and connectivity of fracturing, fissuring and jointing, as well as the type and nature of the fillings in the joint apertures (OLUYIDE A& UDEY, 1965; BIANCHI & SNOW, 1969; ASSEEZ, 1972; ODUSANYA, 1989; ESU, 1993; EDUVIE & OLABODE, 2001).

Considering the limited characteristics of the groundwater reservoirs in the Basement Complex, the full benefit of the aquifer system can only be exploited through a well coordinated hydrogeophysical and geological investigation program of the prospective area. Geoelectrical techniques are powerful tools and play a vital role in groundwater investigations particularly in the delineation of the aquifer configuration in complex geological environments. A planned geoelectrical investigation is capable of mapping an

aquifer system, clay layers, the depth and thickness of aquifers, fissure or fracture location, and qualitatively estimating local groundwater flow (FITZGERMAN & STEWART, 1986; MCNEILL, 1987; OLASEHINDE, 1989) and has been adopted in this study. The most commonly used geophysical technique for groundwater exploration is electrical resistivity (MAZAC et al, 1987) which is aimed at identifying high conductivity anomalies, normally thought to be due to deep weathering. Recent developments in geoelectrical data acquisition and interpretation methodology provide electrical images of subsurface features. A properly calibrated electrical image can be used to infer the aquifer configuration: depth, thickness, horizontal and vertical extent of the aquifers. Investigation involving detail geophysical study for groundwater potential in the area covered by this study is presently non-existence. This exigency inspired this study. Therefore, the primary objective of this study was to determine the groundwater potential and to identify suitable sites/locations for exploration of groundwater in industrial estate Ogbomoso, Southwestern Nigeria.

#### SITE DESCRIPTION

The studied area lies within the crystalline Basement Complex of Nigeria (MACDONALD & DAVIES, 2000). It lies

within latitude  $08^{\circ} 06' 07.4''$  and  $08^{\circ} 06' 25.4''$  and longitude  $004^{\circ} 15' 03.3''$  and  $004^{\circ} 15' 49.0''$ . The study area is located at the outskirts of Ogbomoso South Local Government and shares boundary with Surulere Local Government Area along old Oshogbo road. The study area is accessible with network of roads that surrounds it and very close to Aarada market.

#### HYDROGEOLOGICAL SETTING

According to MACDONALD & DAVIES (2000) who classified the hydrogeology of Sub-Saharan Africa into four provinces, these are: Precambrian basement rocks, volcanic rocks, unconsolidated sediments and consolidated sedimentary rocks (figure 1a). These four provinces are well represented in Nigeria (figure 1b). The study area is located on the Precambrian basement rocks of Southwestern Nigeria which comprise of crystalline and metamorphic rocks over 550 million years old (MACDONALD & DAVIES, 2000).

Unweathered basement rock contains negligible groundwater. However, significant aquifers develop within the weathered overburden and fractured bedrock (MACDONALD & DAVIES, 2000; ALAGBE, 2005). In the soil zone (top soil) of Precambrian basement, permeability is usually high, but groundwater does not exist throughout the year and



dries out soon after the rains end. Beneath the soil zone, the rock is often highly weathered and clay rich, therefore permeability is low. Towards the base of the weathered zone, near the fresh rock interface, the proportion of clay significantly reduces. This horizon, which consists of fractured rock, is often permeable, allowing water to move freely. Wells or boreholes that penetrate this horizon can usually provide sufficient water for consumption (MACDONALD & DAVIES).

Deeper fractures within the basement rocks are also an important source of groundwater, particularly where the weathered zone is thin or absent. These deep fractures are tectonically controlled and can sometimes provide supplies of up to 1 l/s or even 5 l/s. The groundwater resources within the regolith and deeper fracture zones depend on the thickness of the water-bearing zone and the relative depth of the water table. The deeper the weathering, the more sustainable the groundwater (MACDONALD & DAVIES, 2000).

## GEOLOGICAL SETTING

Regionally, the Study area lies within the South Western parts of the Basement rocks, which is part of the much larger Pan-Africa mobile belt that lies in between the West Africa Craton and Congo Craton, suspected to have been

subjected only to a thermotectonic event (ALAGBE, 2005).

In general, the southwestern Nigeria crystalline Basement (figure 1c) can be grouped into three:

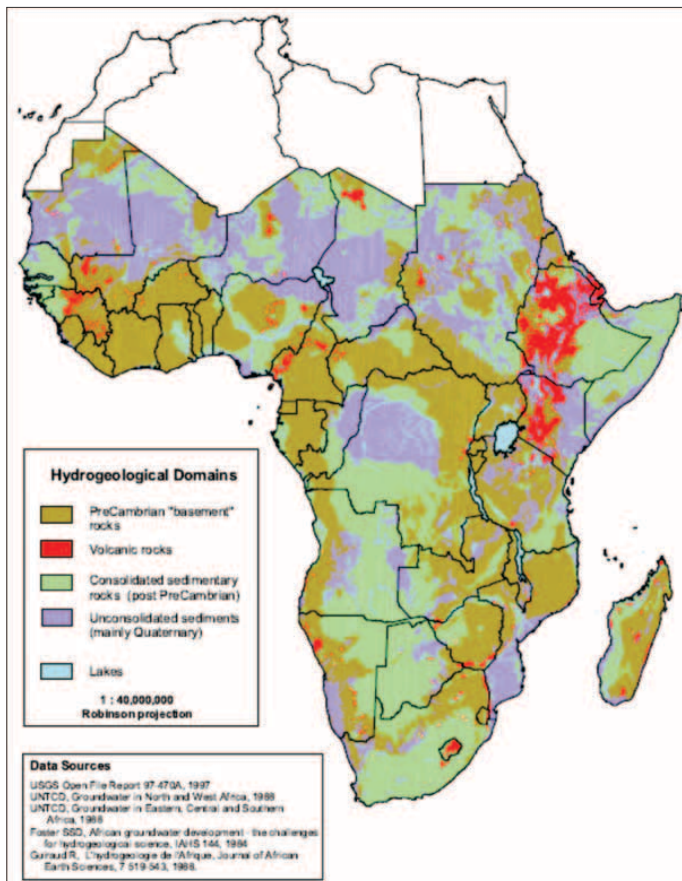
- **The Migmatite-Gneiss Complex:** It compose of Migmatite and gneiss of various composition. Relics of sedimentary rocks such as quartzitic rocks occurring within the group with ages ranging from Pan-Africa (600 million years) to Leonian (RUSS, 1957). They have been metamorphosed in the middle to upper amphibolite facies (AJIBADE et al, 1988).
- **Metasedimentary and Metavolcanic Rocks:** (This is also known as Low grade sediment dominated schist belt) trending N-S which are considered to be Upper Proterozoic (Birimian) in age. The Northwestern basement has well developed schist belts (Green Schist facies) comprising mainly of phyllite, Schist, quartzitic and banded iron formation (BIF). The rocks are considered to be Upper Proterozoic that has been infolded into Migmatite-gneiss complex (TRUSSWELL & COPE, 1963).
- **The Pan-African Older Granite Series:** This intrude both into the Migmatite-gneiss-quartzite complex and the Low grade schist belts. They range widely in age and composition from true granite to grano-

diorite, adamalite and tonalities. Other rocks associated with it are highly hypersthene bearing rocks called charnokites.

Their Rb/Sr ages range between 750 million years and 450 million years (AJIBADE et al 1988), which are considered to be ages of emplacement, classify these rocks as strictly belonging to Pan Africa. Notably among the granite series are Kuseriki gran-

ites (TRUSWELL & COPE, 1963). The above three division is largely based on lithology and does not in anyway reflect the range of Complex field relationship and structures displayed on the rocks.

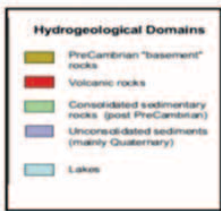
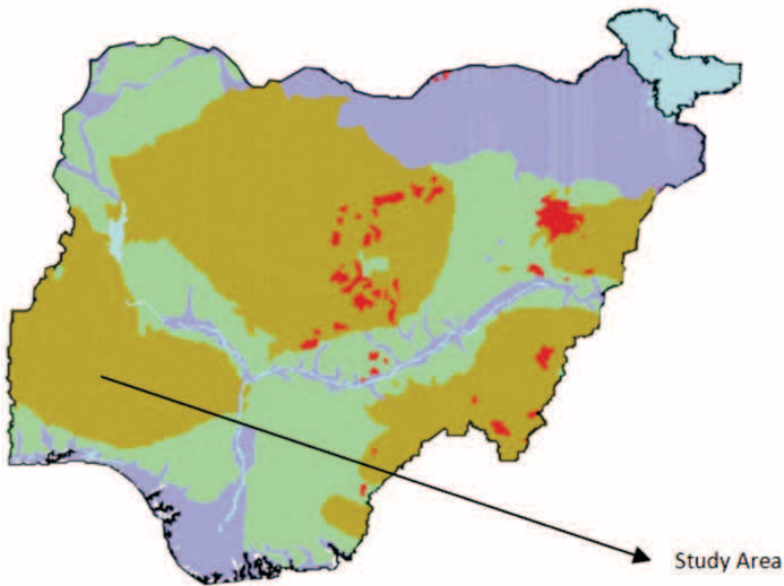
Locally, the study area lies within Ogbomoso and is underlain by rocks of the Precambrian complex with Quartzite and Quartz-Schist and Undifferentiated Gneiss and Migma-



**Figure 1a.** The hydrogeological domains of Sub-Saharan Africa (MACDONALD & DAVIES, 2000).

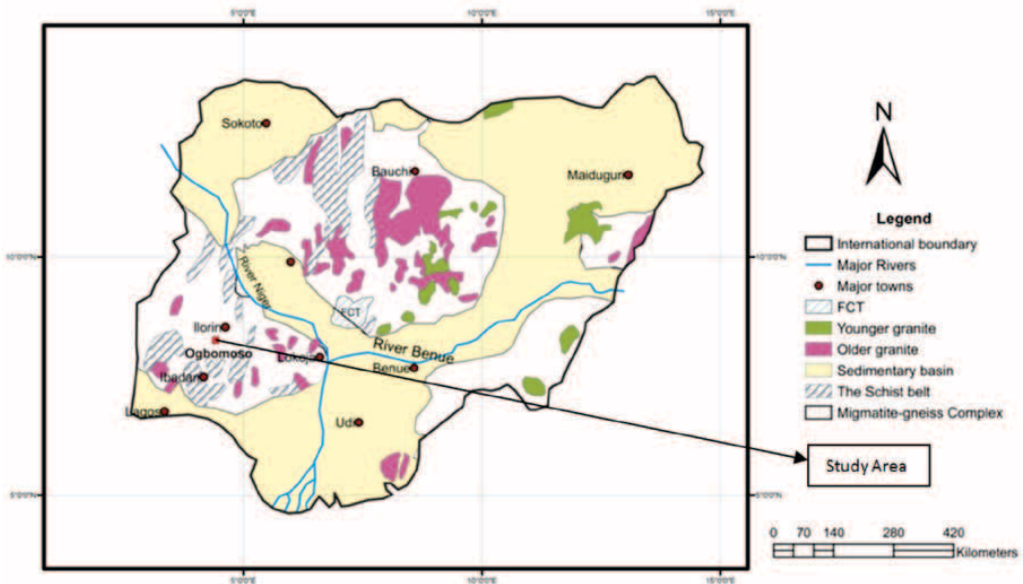
tite (AJIBADE et al., 1988). The rock groups in the area include quartzites and gneisses (AJIBADE et al, 1988). Schistose quartzites with micaceous minerals alternating with quartzofeldspathic ones are also experienced in the area. The gneisses are the most dominant rock type. They occur as granite gneisses and banded gneisses with coarse to medium grained texture. Noticeable minerals include quartz, feldspar and biotite. Pegma-

tites are common as intrusive rocks occurring as joints and vein fillings (RAHAMAN, 1976; AYANTUNJI, 2005). They are coarse grained and weathered easily in to clay and sand-sized particles, which serve as water-bearing horizon of the regolith. Structural features exhibited by these rocks are foliation, faults, joints and microfolds which have implications on groundwater accumulation and movement (AYANTUNJI, 2005).



Source of the map:  
the hydrogeology map of Africa produced by  
MacDonald A.M. And Davies J., 2000.

**Figure 1b.** The hydrogeological domains of Nigeria (extracted from MACDONALD & DAVIES, 2000).



**Figure 1c.** Geological map of Nigeria showing the study area. (Modified after AJIBADE et al, 1988).

### THEORY OF ELECTRICAL RESISTIVITY IN ROCKS

The foundation of electrical resistivity theory is the Ohm's law (GRANT & WEST, 1965) which states that the ratio of potential difference ( $V$ ) between two ends of a conductor in an electrical circuit to the current ( $I$ ) flowing through it is a constant.

$$V = IR \quad (1)$$

Where  $R$  is a constant known as resistance measured in ohms ( $\Omega$ ).

If the conductor is a homogeneous cylinder of length ( $L$ ) and cross sectional area ( $A$ ), the resistance will be proportional to the length and inversely proportional to the area (DUFFIN, 1979).

$$R = \frac{\rho L}{A} \quad (2)$$

Where  $\rho$  is the resistivity measured in ohm-meter ( $\Omega\text{m}$ ).

The earth's material is predominantly made up of silicate, which are basically non-conductors. The presence of water in the pore spaces of the soil and in the rocks enhances the conductivity of the earth when an electrical current ( $I$ ) is passed through it, thus making the rock a semi-conductor.

If the electrical field generated by the current is  $E$  across the length when a potential difference ( $V$ ) is applied, then the potential difference can be defined

(EVWARAYE & MGBANA, 1993) as:

$$V = EL \tag{3}$$

where  $E$  is the electric field strength with dimension of volt per meter (V/m).

If the current electrode is taken to penetrate a small hemisphere of radius  $r$ , then the area of the hemisphere becomes  $2\pi r^2$ .

Substituting for  $E$  and integrating Equation 3 gives:

$$\Delta V = \int E.dr. \text{ (DUFFIN, 1979)} \tag{4}$$

$$\text{or } \Delta V = \frac{I\rho}{2\pi r} \tag{5}$$

$$\text{and } \rho = \Delta V.2\pi r \tag{6}$$

Since the earth is not homogeneous, Equation 6 is used to define an apparent resistivity  $\rho_a$  which is the resistivity the earth would have if it were homogeneous (GRANT & WEST, 1965). Equation 6 can be written in a general form as:

$$\rho_a = \frac{\Delta V}{I}.G \tag{7}$$

where  $G$  is a geometrical factor fixed for a given electrode configuration.

The Schlumberger electrode configuration has been used in this study. In this arrangement, current is injected into the earth through two electrodes which create a potential field which is detected by

another pair of electrodes. The geometrical factor for the schlumberger electrode configuration is given by:

$$G = \frac{\pi((\frac{AB}{2})^2 - (\frac{MN}{2})^2)}{2(\frac{MN}{2})} \tag{8}$$

where  $AB$  is the distance between two current electrodes, and  $MN$  is the distance between two potential difference.

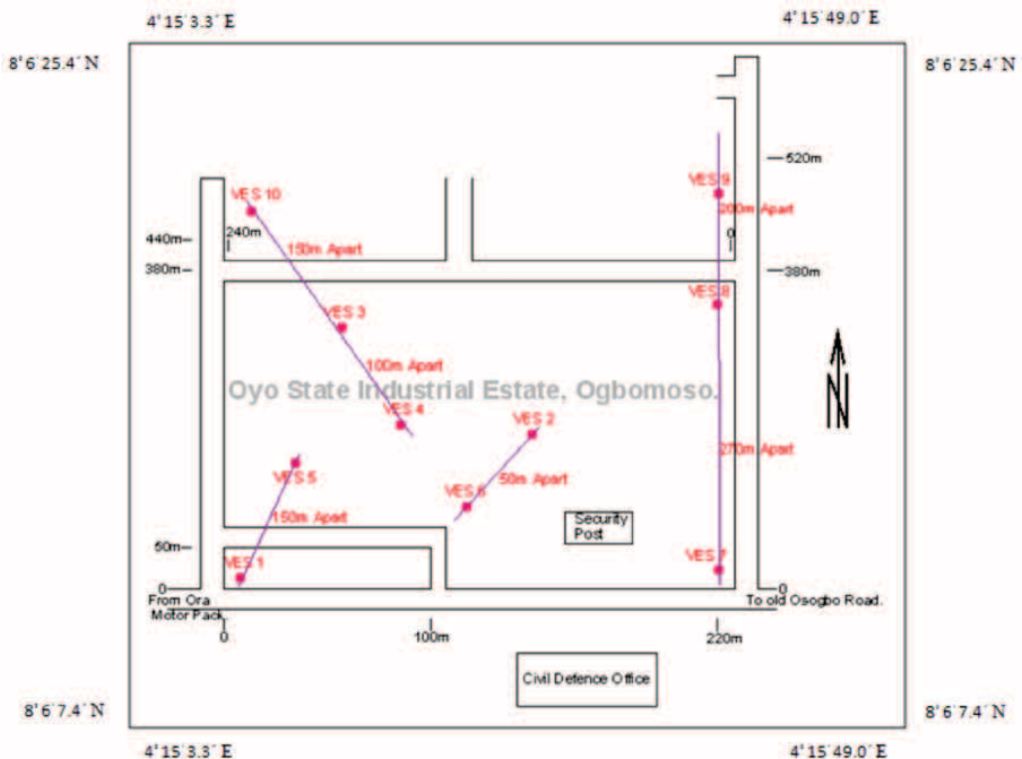
#### MATERIALS AND METHODOLOGY

A four day geophysical survey was carried out from 13th to 16th October, 2011 using the electrical resistivity method. The survey was conducted with R 50 Resistivity meter. A total of 10 Vertical Electrical Sounding (VES) stations were occupied randomly to cover the area of study (Figure 2). The schlumberger array with maximum electrode spacing ( $AB$ ) of 130 m to 200 m was used for the field resistance measurements. The resistivity values were determined and plotted on a double logarithmic graph paper for quick check on the field. The VES curves were generated by applying the conventional curve matching (ZOHDY, 1973; ZOHDY & MABOY, 1974; PATRA & NATH, 1999).

Parameters such as apparent resistivity and thickness obtained from partial curve matching were used as input data for computer iterative modeling

using the WinResist software (VANDER VELPEN, 2004). The VES curves generated gives the thickness and the resistivities of different layers. The depth sounding curves were then classified according to the resistivity contrasts between the layers as H, K, A, Q or multiples thereof, following the classification by KELLER & FRISCHNECHT (1970) and PATRA & NATH (1999). The modeling produced series of curves as shown in figure 3(a–b). Nine out of the ten curves were H-type ( $\rho_1 > \rho_2 < \rho_3$ ) while the remaining one showed KH-type ( $\rho_1 < \rho_2 > \rho_3 < \rho_4$ ). Surfer 8 software (Surfer 8, 2002) was further used

on personal computer to produce 3-dimensional view of Overburden isopach map, overburden anisotropic coefficient map, weathered layer isothickness map, weathered layer iso-resistivity map, weathered layer transverse resistance map, and bedrock relief map in order to evaluate the groundwater potential of the study area. Surfer 8 program is software that helps to produce 2-Dimensional and 3-Dimensional images. Geoelectric layers parameters was input into this software to produce 3-Dimensional images of subsurface in order to determine the groundwater potential of industrial estate Ogbomoso.

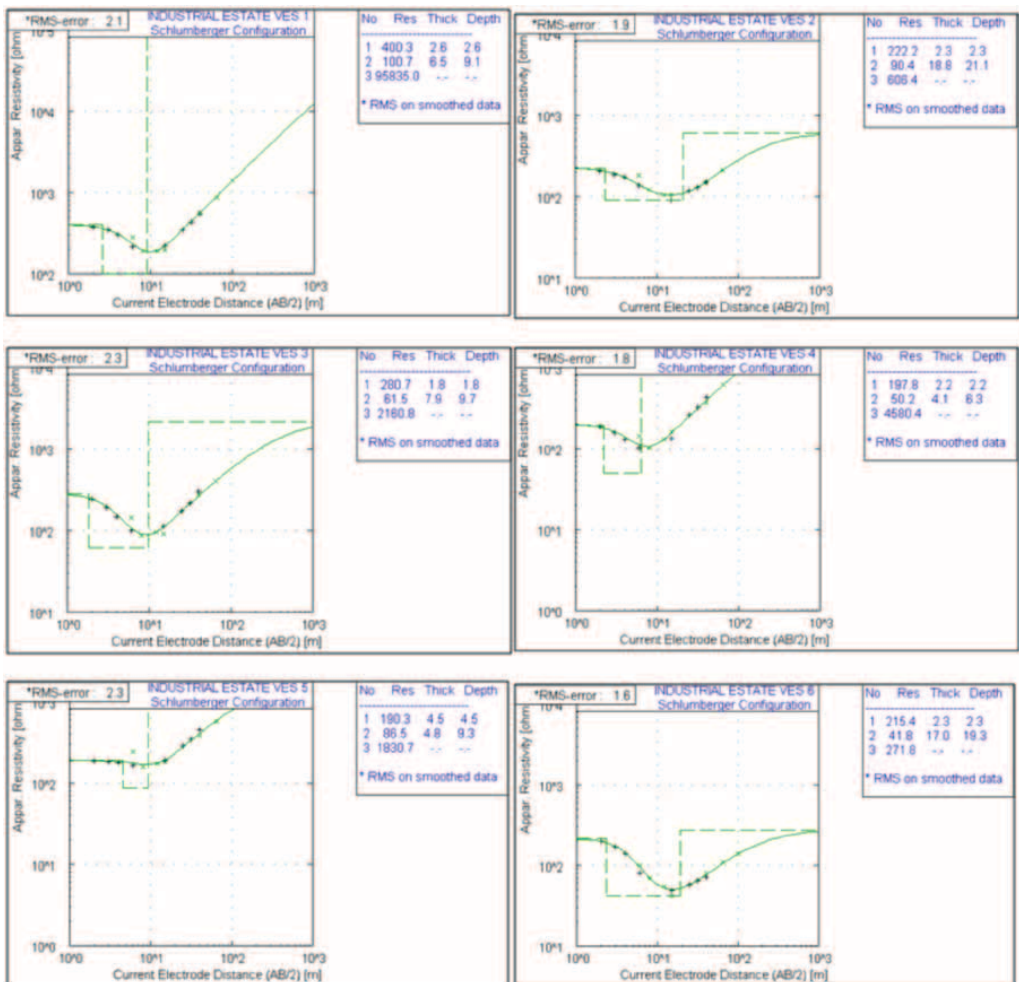


**Figure 2.** Layout map of Vertical Electrical Sounding stations.

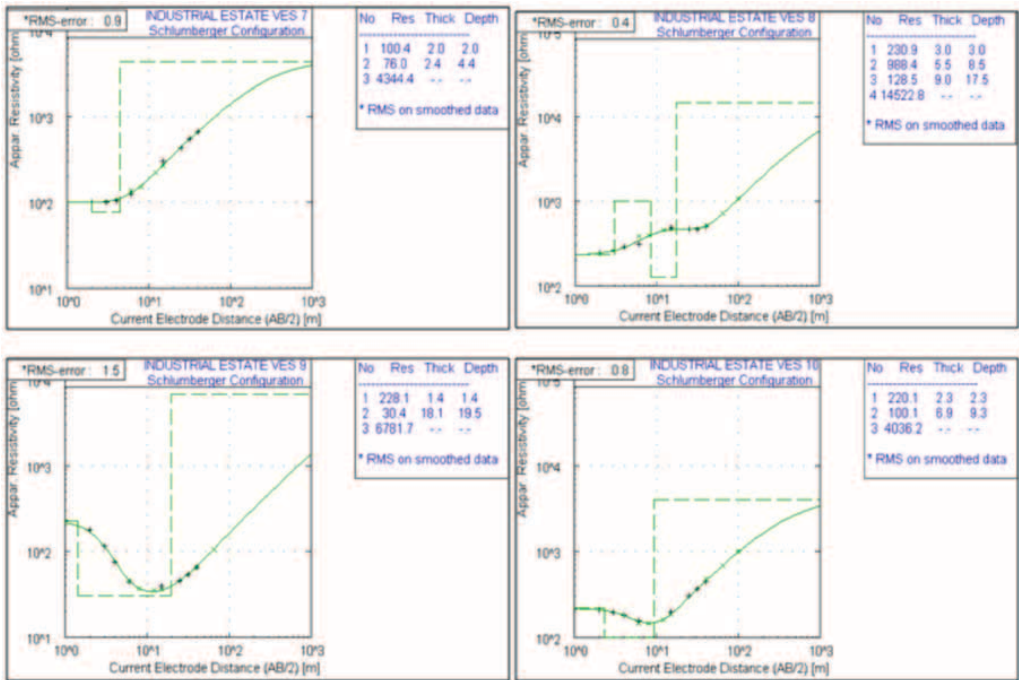
**RESULTS AND DISCUSSION**

The presence of groundwater in any rock presupposes the satisfaction of two factors: adequate porosity and adequate permeability. On account of their crystalline nature, the metamorphic and igneous rocks of the Basement Complex satisfy neither of these requirements. Basement complex rocks are thus con-

sidered to be poor aquifers because of their low primary porosity and permeability necessary for groundwater accumulation (DAVIS & DE WEIST, 1966). However, secondary porosity and permeability imposed on them by fracturing, fissuring, jointing, and weathering through which water percolates make them favourable for groundwater storage (OMORINBOLA, 1979).



**Figure 3(a).** The modeled curve for VES 1 to VES 6



**Figure 3(b).** The modeled curve for VES 7 to VES 10.

The modeled curves showed three layers in nine of the VES stations (i.e. VES 1, 2, 3, 4, 5, 6, 7, 9 and 10) and four layers in the remaining one (i. e. VES 8) (figure 3a–b). The result showed that 60 % of the VES stations have thin overburden and fresh basement rocks (i.e. VES 1, 3, 4, 5, 7 and 10), 20 % of the VES stations have thick overburden and fresh basement rocks (i.e. VES 8 and 9) while the remaining 20 % of the VES stations have thick overburden and fractured basement rocks (i. e. VES 2 and 6).

From the results, VES 2 and 6 are the best location for groundwater

prospect because of the thick overburden and fracture in the basement (WRIGHT, 1990; MEJU et al., 1999). VES 8 and 9 could be considered as another location for groundwater exploration because BENSON & JONES (1988) and LENKEY et al. (2005) reported that boreholes should be sited where the regolith is thickest.

Summary of the formation of the layer parameters is presented in table 1 while summary of classification of the resistivity sounding curves is presented in table 2.



**Table 1.** Summary of the formation of layer parameters.

Location	Layer 1		Layer 2		Layer 3		Layer 4	
	$\rho_1/(\Omega\text{ m})$	$h_1/\text{m}$	$\rho_2/(\Omega\text{ m})$	$h_2/\text{m}$	$\rho_3/(\Omega\text{ m})$	$h_3/\text{m}$	$\rho_4/(\Omega\text{ m})$	$h_4/\text{m}$
VES 1	400.3	2.6	100.7	6.5	95835.0	-	-	-
VES 2	222.2	2.3	90.4	18.8	606.4	-	-	-
VES 3	280.7	1.8	61.5	7.9	2160.8	-	-	-
VES 4	197.8	2.2	50.2	4.1	4580.4	-	-	-
VES 5	190.3	4.5	86.5	4.8	1830.7	-	-	-
VES 6	215.4	2.3	41.8	17.0	271.8	-	-	-
VES 7	100.4	2.0	76.0	2.4	4344.4	-	-	-
VES 8	230.9	3.0	988.4	5.5	128.5	9.0	14522.8	-
VES 9	228.1	1.4	30.4	18.1	6781.7	-	-	-
VES 10	220.1	2.3	100.1	6.9	4036.2	-	-	-

**Table 2.** Classification of the resistivity sounding curves.

Curve types	Resistivity model	Model frequency	VES Locations
H	$\rho_1 > \rho_2 < \rho_3$	9	1, 2, 3, 4, 5, 6, 7, 9, 10
KH	$\rho_1 < \rho_2 > \rho_3 < \rho_4$	1	8
Total		10	

**Groundwater Potential Evaluation**

The groundwater potential of a basement complex area is determined by a complex inter-relationship between the geology, post emplacement tectonic history (fractures), weathering processes and depth, nature of the weathered layer, groundwater flow pattern, recharge and discharge processes (OLORUNFEMI et al, 1999). The groundwater potential of the study area was evaluated based on maps (i.e. overburden thickness, anisotropic coefficient, weathered layer isothickness, weathered layer iso-resistivity, transverse resistance and bedrock relief maps) generated from the VES interpretation

results. The characteristic geoelectric parameters enabled the groundwater potential rating at each VES location. These maps are as presented below.

**Overburden Thickness Isopach Map**

The depth to the basement (overburden thickness) beneath the sounding stations were plotted and contoured at 1m interval as shown in figure 4. This was done to enable a general view of the aquifer geometry of the surveyed area. The overburden is assumed to include the topsoil, the lateritic horizon and the clay/weathered rock. The values range from 4.4 m to 21.1 m. Areas with thick overburden corresponding to basement

depression and are known to have high groundwater potential particularly in the basement complex area (WRIGHT, 1990; OLORUNFEMI & OKHUE, 1992; MEJU et al., 1999).

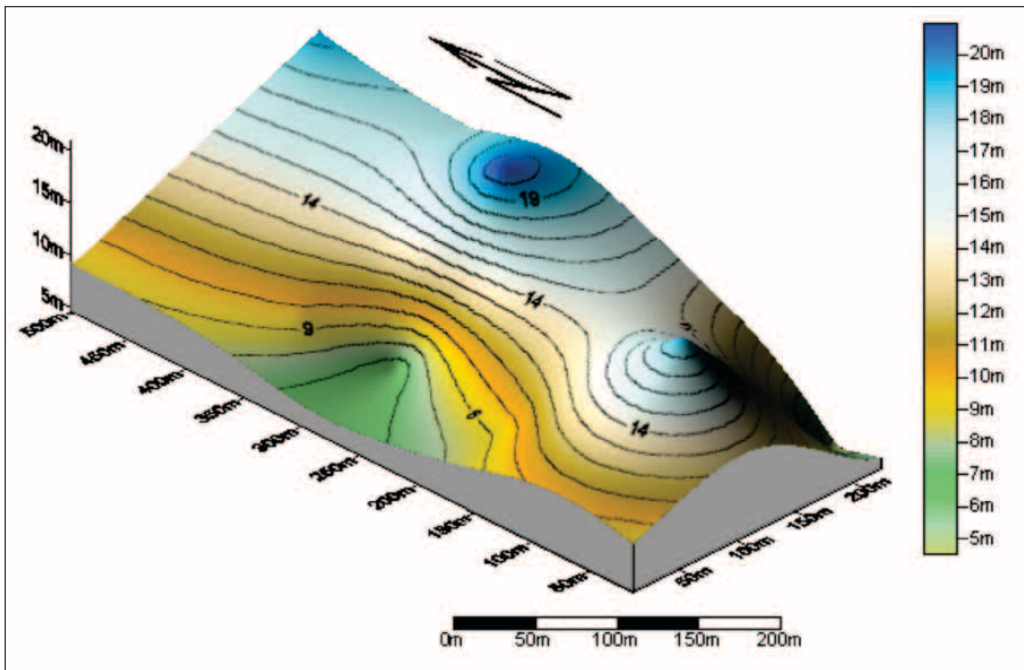
The Southern (i. e. VES 6), Northeastern (i. e. VES 8 and VES 9) and Eastern (i. e. VES 2) side of the study area has thick overburden thickness while

the Western and Southeastern side of the study area showed thin overburden thickness. The Southern, Northeastern, and the Eastern side of the study area are the promising locations for groundwater prospect.

Since the yield of a well in the Basement Complex is expected to have a positive correlation with the depth

**Table 3.** Aquifer potential as a function of the depth to bedrock (OLAYINKA et al., 1997).

Overburden Thickness (m)	
Range	Weighting
<5	2.5
5–10	5
10–15	7.5
>15	10



**Figure 4.** Overburden thickness isopach map

to bedrock, weights that are directly proportional to the overburden thickness have been assigned (OLAYINKA et al., 1997). These weights range from a minimum of 2.5 for thickness less than 5 m to a maximum of 10 for overburden thickness exceeding 15 m (table 3).

**Coefficient of Anisotropy of the Overburden**

The overburden’s coefficient of anisotropy ( $\lambda$ ) was calculated for each VES station using the layer resistivities and thicknesses (OLORUNFEMI & OKHUE, 1992);

$$\lambda = \sqrt{\frac{\rho_t}{\rho_l}} = \sqrt{\frac{\sum_{i=1}^{n-1} h_i \rho_i \sum_{i=1}^{n-1} \frac{h_i}{\rho_i}}{(\sum_{i=1}^{n-1} h_i)^2}} \tag{9}$$

where  $\rho_t$  is the transverse resistance,  $\rho_l$  is the longitudinal resistance,  $i$  is the summation limit varying from 1 to  $n - 1$ ,  $h_i$  is the  $i$ th layer thickness and  $\rho_i$  is the  $i$ -th layer resistivity.

The  $\lambda$  values were plotted and contoured. This was done in order to know the areas that are good for groundwater prospects. Areas which show ridges on the map will be promising zones for groundwater prospects while areas which show depressions on the map will not be suitable for groundwater prospects. The resulting overburden coefficient of anisotropy map (figure 5) shows  $\lambda$  values ranging from 1.0 to 1.45 with a mean value of 1.16. Vividly, the Northeastern and to the base

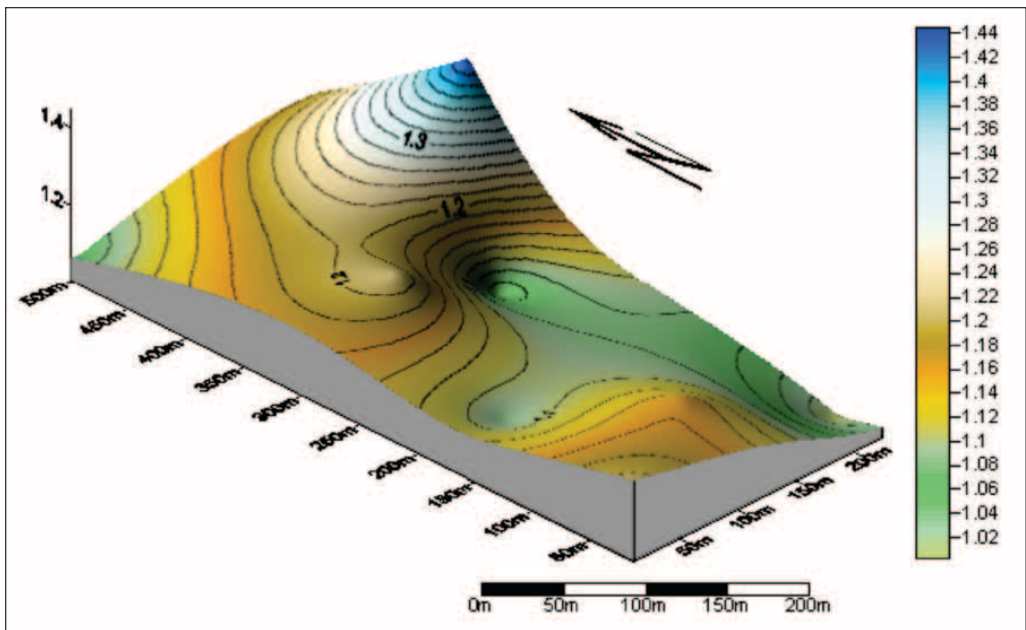


Figure 5. Overburden anisotropy coefficient map.

**Table 4.** Aquifer potential as a function of overburden anisotropic coefficient.

Anisotropy Coefficient ( $\lambda$ )	
Range	Weighting
<1	2.5
1–1.5	5
1.5–2	7.5
>2	10

of the Eastern side of the study area showed that overburden's coefficient of anisotropy ( $\lambda$ ) is high. Also, some peaks were observed at Southern to the Southwestern part of the study area. These areas with peaks are the promising locations for groundwater prospect.

OLORUNFEMI et al, (1991) gives the mean coefficient of anisotropy of igneous and metamorphic rocks of the Basement Complex of southwestern Nigeria as 2.12 and 1.56 respectively and that groundwater yields increase linearly with increase in  $\lambda$  (OLORUNFEMI & OLORUNNIWO, 1985; OLORUNFEMI et al, 1991; OLORUNFEMI & OKHUE, 1992). All the values of  $\lambda$  obtained fall within the range of areas underlain by metamorphic rocks in the southwestern Nigeria.

Since the yield of a well in the Basement Complex is expected to have a positive correlation with the value of the overburden anisotropic coefficient, weights, ranging from a minimum of 2.5 for  $\lambda$  less than 1 to a maximum

of 10 for  $\lambda$  exceeding 2 have been assigned (table 4).

#### ***Weathered Layer Isothickness Map***

The weathered layers as defined in this work are materials constituting the regolith, straddled in between the topsoil or laterite and fractured or fresh bedrock. The thickness of these lithological materials varies between 2.4 m and 18.8 m. This was determined from the layer interpretation of the sounding results. The weathered layer isopach map was produced using a contour interval of 1 m (figure 6). The map was produced with a view to observing how the weathered basement layer considered to be the major component of the aquifer in the study area varied from place to place.

The weathered layer is seen to be thickest at Eastern, some part of the Northeastern region and Southern part of the study area, groundwater potential is most prominent here. The Western and peak of the Southeastern part of the study area showed a very thin weathered layer.

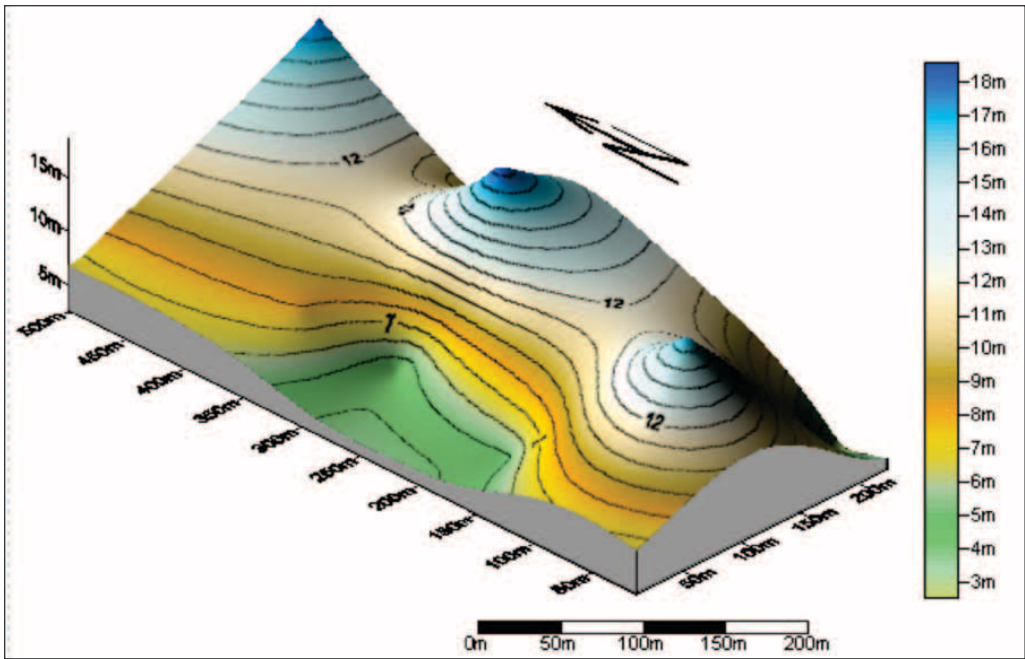


Figure 6. Weathered layer isothickness map

#### *Weathered Layer Isoresistivity Map*

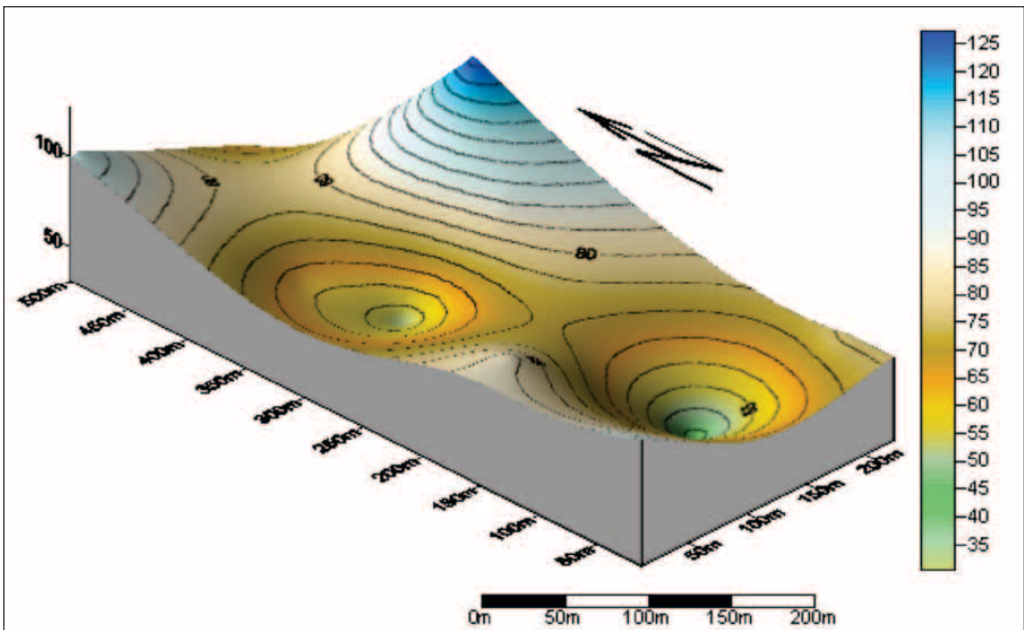
In order to have an insight to the groundwater potentials of the study area, an aquifer resistivity map (figure 7) was produced from the interpreted VES data results of this work. The resistivity value of the aquifers at each VES site location was plotted and contoured at  $5 \Omega \text{ m}$ . The map was produced in order to distinguish high water-bearing weathered layer from low water-bearing ones, and to find out whether or not the degree of weathering /saturation varies from point to point in the study area.

As shown on the map, the resistivity value of the aquifer is highest at the

Northeastern (i. e. VES 8 and VES 9) part of the study area which falls within medium potential condition (table 5). However, the Southern part (i. e. VES 6) and the Western part (i. e. VES 4) of the study area showed low resistivity values. The Southern part might be the most promising location for groundwater prospect because of the results from VES curve 6 (WRIGHT, 1990; MEJU et al., 1999). The Western part (i.e. VES 4) could be considered as another promising area for groundwater prospect but because of its thin overburden (LENKEY at al., 2005), the water present in the aquifer might not be able to serve the industrial purposes in the time of prolonged dry season.

The electrical resistivity of the saprolite layer overlying the basement is controlled by the parent rock type, climatic factors, as well as the clay content. A low resistivity of the order of less than 20 Ω m is indicative of a clayey regolith (CARRUTHERS & SMITH, 1992; Olayinka et al, 1997).

This reduces the permeability and thus lowers the aquifer potential. Weights are assigned to the weathered layer resistivity values according to WRIGHT, (1992). Table 5 summarized the optimum aquifer potentials associated with the saprolite resistivities.



**Figure 7.** Weathered layer iso-resistivity map

**Table 5.** Aquifer potential as a function of the weathered layer resistivity (modified after WRIGHT, 1992).

Weathered Layer Resistivity (Ω m)		
Range	Aquifer Characteristics	Weighting
<20	Clay with limited potential	7.5
21–100	Optimum weathering and good groundwater potential	10
101–150	Medium conditions and potential	7.5
151–300	Little weathering and poor potential	5
>300	Negligible potential	2.5

### ***Weathered Layer Transverse Resistance Map***

Aquifer transmissivity has been found to be a very powerful means of confirming zones of prolific aquifers. This parameter is defined in hydrogeology, as the product of aquifers hydraulic conductivity (or permeability) and its thickness.

$$T = K \times h \quad (10)$$

where  $T$  is transmissivity,  $K$  is hydraulic conductivity and  $h$  is the thickness of the aquifer (TODD, 1980).

According to MAILLET, 1974 transverse resistance ( $R_T$ ) of a layer as of the Dar-Zarrouk parameters, is defined as:

$$R_T = h \times \rho \quad (11)$$

Where,  $h$  and  $\rho$  are thickness and resistivity respectively, of the layer.

The relationship between transmissivity ( $T$ ) and transverse resistance ( $R_T$ ) is meaningful, simply because hydraulic conductivity ( $K$ ) and resistivity ( $\rho$ ) have a direct linear relationship (NIWAS & SINGHAL, 1981). Combining the two equations, we have

$$T = \frac{K}{\rho} \times R_T = K\sigma \times R_T \quad (12)$$

This relationship is suitable for determination of aquifer transmissivity, as the ratio  $K/\rho = K\sigma$  is assumed to be constant in areas with similar geologic setting and water quality (NIWAS & SINGHAL, 1981; ADERINTO, 1986; ONUOHA & MBAZI, 1988; ONU, 2003).

Thus knowing the value of  $K$  for some existing boreholes and the value of  $\sigma$  extracted from the sounding interpretation for the aquifers at the borehole locations, the transmissivity of the aquifer can be computed.

These established relationships were utilized with the hydraulic conductivity ( $K$ ) values of boreholes near Northwestern side (i.e. some metres away from VES 10), near Northeastern side (i. e. some metres away from VES 9), and the other two boreholes were located towards the Southern part of the study area (i. e. behind the Civil defence office). The hydraulic conductivity ( $K$ ) were determined to be (6.62, 11.99, 11.42 and 15.54) m/d respectively after pumping test by D' Strata Drilling Company and the  $K\sigma$  of these points were found to be 0.097, 0.097, 0.1164 and 0.1034 respectively. An average of 0.10344 was used for the entire study area. The transmissivity at each VES station was determined by multiplying average  $K\sigma$  with corresponding transverse resistance,  $R_T$  and the variation of transmissivity across the aquiferous zone of the investigated area is shown in figure 8.

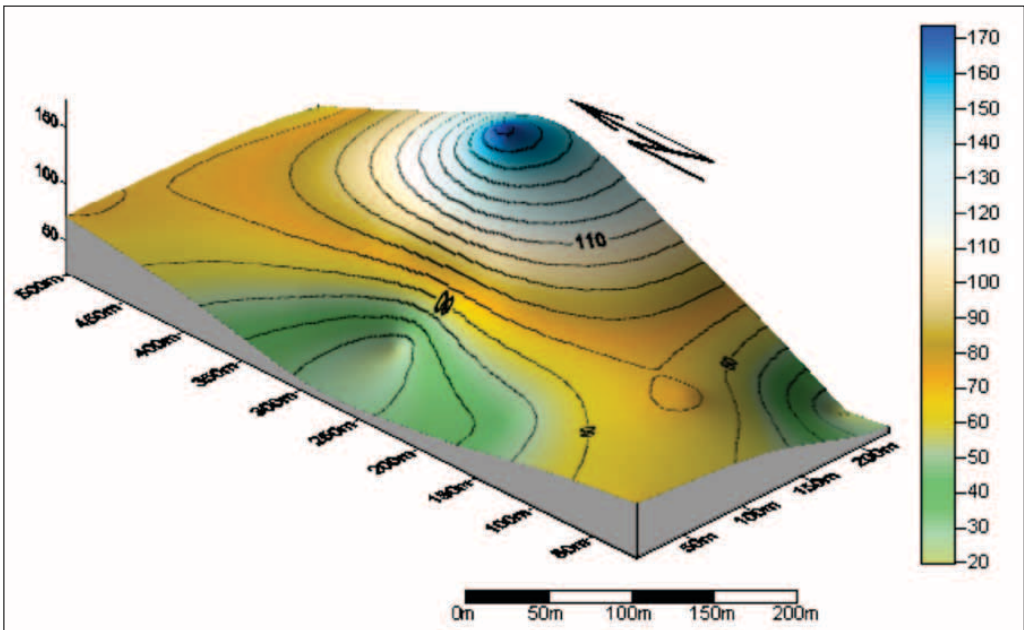
On a purely empirical basis, it can be admitted that the transmissivity of an aquifer is directly proportional to its transverse resistance (HENRIET, 1975). Therefore, transverse resistance maps is used in determination of zones with

high groundwater potential (TOTO et al, 1983; BRAGA et al, 2006) and suitable for drilling wells.

The Eastern flank of the study area has transverse resistance corresponding to high transmissivity which in turn means greater water potential. Also, a little peak is experienced at the Southern part of the study area, this location

is another promising area for groundwater prospect in the study area. However, the Western and the Southeastern flank generally has low transmissivity.

On a purely empirical basis, it can be admitted that the transmissivity of an aquifer is directly proportional to its transverse resistance (HENRIET, 1975; HADI, 2009). Hence, there exists a lin-



**Figure 8.** Weathered layer transverse resistance map.

**Table 6.** Aquifer potential as a function of the weathered layer transverse resistance.

Transverse Resistance ( $\Omega \text{ m}^2$ )	
Range	Weighting
<400	2.5
400–1000	5
1000–2000	7.5
>2000	10



ear relationship between groundwater potential and the transverse resistance of an aquifer (ADERINTO, 1986). Table 6 gives a summary of the variation of aquifer potential with transverse resistance.

### ***Bedrock Relief Map***

The bedrock relief map (figure 9) is a contoured map of the bedrock elevations beneath all the VES stations. These bedrock elevations were obtained by subtracting the overburden thicknesses from the surface elevations at the VES stations. The bedrock relief map generated for the locations shows the subsurface topography of the bedrock across the surveyed area. Bedrock relief map helps to see vividly the suspected areas for groundwater prospects. Areas with basement depressions on the map serve as collecting trough for groundwater which will be the best zones for groundwater prospects. Bedrock relief has been used by OKHUE & OLORUNFEMI (1991), OLORUNFEMI & OKHUE (1992), DAN-HASSAN & OLORUNFEMI (1999), OLORUNFEMI et al, (1999) and BALA & IKE (2001) to investigate into groundwater prospects at Ile- Ife SW, Kaduna North Central, Akure SW and Gusau NW part of Nigeria respectively. Procedures used by them have been adopted under this subsection in order to get the promising areas for groundwater prospects at Industrial Estate Ogbomoso SW Nigeria.

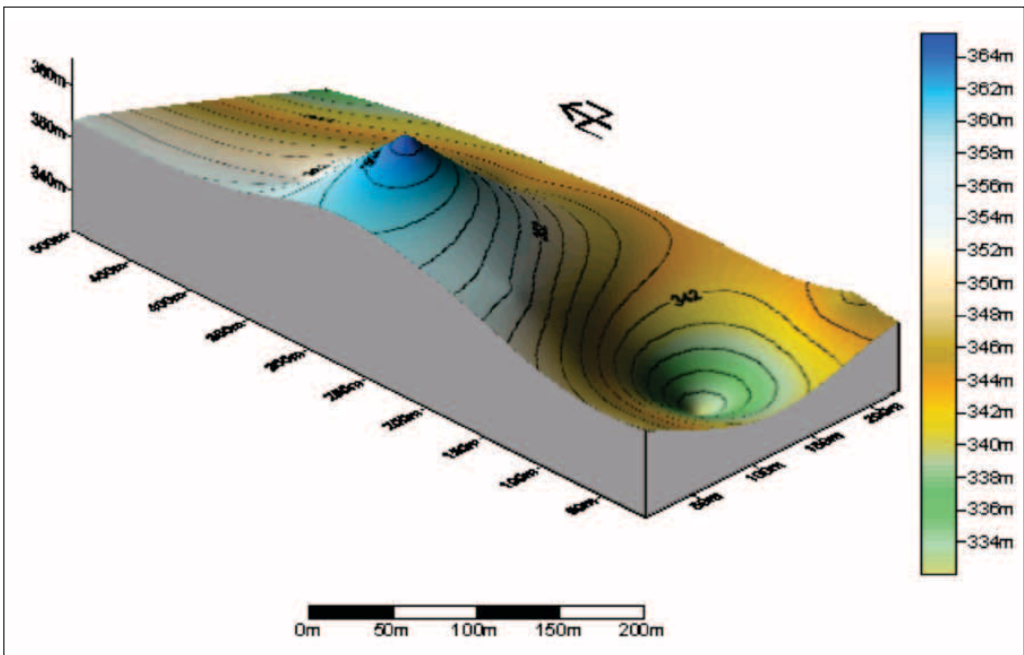
The map shows series of basement lows/depressions and basement highs/ridges. Southern, Eastern and Northeastern part (i. e. VES 2, 6, 8 and 9) are the designated areas for the depressions while Northwestern, Western, Southwestern and Southeastern part (i. e. VES 1, 3, 4, 5 and 7) are ridges zones. The depression zones are noted for thick overburden cover while the basement high/ridge zones are noted for thin overburden cover. OMOSUYI & ENIKANSELU (1999) findings revealed that depressions zone in the basement terrain serves as groundwater collecting trough especially water dispersed from the bedrock crests. Thus, the zones with basement depressions are priority areas for groundwater development in the study locations.

If the bedrock has a low resistivity, a high aquifer potential could be inferred as result of expected high fracture permeability. Bedrock resistivities of the study area from figure 3a–b are as given below: VES 1 = 95835.0  $\Omega$  m, VES 2 = 606.4  $\Omega$  m, VES 3 = 2160.8  $\Omega$  m, VES 4 = 4580.4  $\Omega$  m, VES 5 = 1830.7  $\Omega$  m, VES 6 = 271.8  $\Omega$  m, VES 7 = 4344.4  $\Omega$  m, VES 8 = 14522.8  $\Omega$  m, VES 9 = 6781.7  $\Omega$  m and VES 10 = 4036.2  $\Omega$  m. The maximum weight of 10 is therefore assigned to cases where the resistivity of the bedrock is less than 750  $\Omega$  m. As the resistivity of

the bedrock increases, there would be a reduction in the influence of weathering, with a corresponding lowering of the aquifer potential (OLAYINKA et al, 1997). Table 7 gives a summary of the variation of aquifer potential with bedrock resistivity.

**Final Groundwater Potential Map of the Study Area**

Final groundwater potential map of the study area was produced in order to draw the final conclusion from the evaluated maps. The weights that have been assigned in Table 1 – Table 7 were used to get the weights of Overburden Thick-



**Figure 9.** Bedrock relief map.

**Table 7.** Aquifer potential as a function of bedrock resistivity.

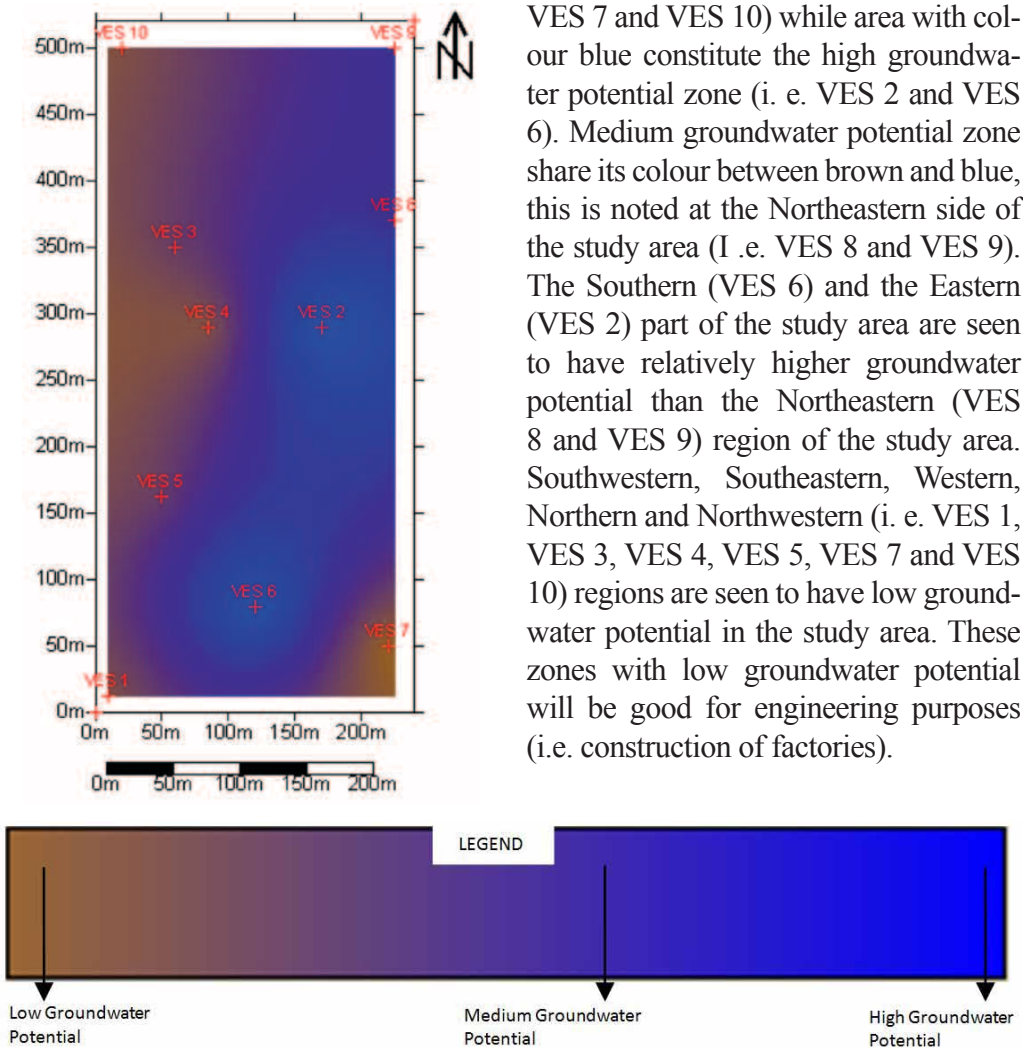
Bedrock Resistivity ( $\Omega$ m)		
Range	Aquifer Characteristics	Weighting
<750	High fracture permeability as a result of weathering; high aquifer potential	10
750–1500	Reduced influence of weathering; medium aquifer potential	7.5
1500–3000	Low aquifer potential	5
>3000	Little or no weathering of the bedrock; negligible potential	2.5

ness, Anisotropy Coefficient, Weathered Layer Resistivity, Transverse Resistance and Bedrock Resistivity of the study area.

A single weighted average is then determined from the geometric mean of the five weights to produce the 2-Dimen-

sional groundwater potential map of the investigated area (figure 10). The map presents local groundwater prospects of the study area which is zoned in to high, medium and low groundwater potentials.

Area with colour brown on the map constitute the low groundwater potential zone (i. e. VES 1, VES 3, VES 4, VES 5, VES 7 and VES 10) while area with colour blue constitute the high groundwater potential zone (i. e. VES 2 and VES 6). Medium groundwater potential zone share its colour between brown and blue, this is noted at the Northeastern side of the study area (I. e. VES 8 and VES 9). The Southern (VES 6) and the Eastern (VES 2) part of the study area are seen to have relatively higher groundwater potential than the Northeastern (VES 8 and VES 9) region of the study area. Southwestern, Southeastern, Western, Northern and Northwestern (i. e. VES 1, VES 3, VES 4, VES 5, VES 7 and VES 10) regions are seen to have low groundwater potential in the study area. These zones with low groundwater potential will be good for engineering purposes (i.e. construction of factories).



**Figure 10.** Final groundwater potential map of the study area

## CONCLUSION

Though the study area was assigned as an industrial estate, as long as water still remains one of our essential amenities in life, the groundwater potential evaluation in the industrial estate Ogbomoso cannot be overlooked. Ignorantly without carrying out geophysical survey, the building contractor might have decided to build on the promising areas for groundwater exploration which will lead to scarcity of groundwater in the study area. Also, building of factories on promising areas for groundwater exploration is even disastrous to the users in the future.

The study has been able to highlight the importance of resistivity method in effective hydrogeologic characterization and groundwater exploration. This study has proved to be quite successful for mapping outcrop types, structural formations and fractures which would not have been observed at the surface. The presence of weathered layer and fractured basement are key components of aquifer system and zone of groundwater accumulation in industrial estate, Ogbomoso. A multi-dimensional approach to this study (that is modeled curves and the maps presented for groundwater potential evaluation) has made the study both very qualitative and quantitative as information missed by any of the methods is revealed by the other and thereby necessitating justifiable conclusions.

It can be concluded that the low resistivity and significantly thick weathered rock/clay and the fractured basement constitute the aquifer in this area. Results from this study have revealed that the Southern and Eastern parts of the study area are the most promising region for borehole development. However, Northeastern region of the study area can also be considered as fair for borehole development as it has been shown from Figure 10.

It is recommended that detailed work be done in this industrial estate using other relevant geophysical methods so as to confirm the fractures predicted and to elucidate the patterns of the fractures.

## Acknowledgements

The corresponding author is grateful to Mr. E. O. and Mrs. C. J. Adagunodo, Miss T. O. Ayinla, Prof. Bayo Ajulo, and Mrs V. A. Ajulo (nee Adagunodo) for the financial support in the course of carrying out this research.

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## Physicotechnical substantiation of parameters of blasting operations in deep open pit mines

### Fizikalnotehniška utemeljitev parametrov miniranja v globokih površinskih kopih

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**Abstract:** Physicotechnical substantiation of parameters of blasting operations has been developed giving due consideration to the effect of increasingly complicated factors of deep open pit mines of Uzbekistan on efficiency of mining operations, protection of the rock solid and engineering structures from seismic load of bulk blasts, improving safety in production and use of emulsion blasting explosives. There has been developed an algorithm of calculation of rational elements of placing of blasthole BE charge and size composition of broken rocks. Researches have been made to improve formulation of matrix emulsion and emulsification process of feedstock solutions. A procedure of high bench blasting has been developed. A blasting procedure for rocks with different bastards has been developed. A seismically safe for adjacent protected objects method of rock blasting without decreasing rock breaking effect has been recommended. Based on researches and analysis of risk level of EBE plant for the purpose of unconditional provision of safe production of EBE a comprehensive safety. System has been developed for safe operation of the EBE plant.

**Izveček:** Fizikalnotehniška utemeljitev parametrov miniranja je bila izvedena ob vsestranskem upoštevanju naraščajoče zapletenih razmer v čedalje globljih površinskih kopih v Uzbekistanu in z ozirom na učinkovitost minerskih operacij ter ohranjanje obstojnosti kamnine in varnosti tehničnih objektov v razmerah seizmičnih vplivov zaradi masovnega miniranja in glede na zagotavljanje varnosti pri izdelavi

in uporabi emulzijskih minerskih eksplozivov. Razvit je bil algoritem za izračun elementov pri nameščanju eksplozivnih nabojev v minskih vrčinah z ozirom na želeno zdrobljenost dane kamnine. Opravljene so bile raziskave z namenom izboljšati pripravo matrične emulzije eksplozivov iz surovinskih raztopin. Razvit je bil postopek miniranja na visokih etažah in dalje, postopek miniranja v kamninah z različnimi trdimi vključki. Predlagana je metoda miniranja, ki je seizmično varna za varovane objekte brez zmanjševanja učinkovitosti drobljenja kamnin. Na osnovi raziskav in analize tveganja delovanja proizvodne postaje za varno pripravo emulzijskih eksplozivov je bil izdelan celovit varnostni sistem za varno obratovanje take postaje.

**Key words:** deep open pit mines, increasingly complicated factors, efficiency of mining operations, bulk blasts, parameters of blasting operations.

**Ključne besede:** globoki površinski kopi, čedalje bolj zapletene razmere, učinkovitost rudarjenja, masovno miniranje, parametri miniranja

## INTRODUCTION

Development of mining industry in Uzbekistan is inseparably associated with development of mineral deposits by open-pit method. As is known, the considerable part of open pits for opencast mining of minerals has entered a category of "deep" and the tendency still persists. Parameters of current open pit mines have essentially increased. Large deep Muruntau and Kalmakyr open pits located on the territory of Uzbekistan are in the world mining practice unique for complexity and novelty of the solved in the course of their creation and operation scientific and technical problems defined by peculiarities of mining-and-geological and mining-technical conditions of deposits development. There are pre-

design options of profitable mining and further development of Muruntau and Kalmakyr open pits to the depth of 900–1000 m.

Meanwhile, it is known that with increasing depth of open-cast mining of ore deposits up to the utmost economically expedient level there become more sophisticated mining-and-geological and mining-technical conditions of operations, water content and fissuring of rocks increase, influence of mine depth on ore resistibility to explosive rupture grows, and requirements to safety of engineering structures installed on deep horizons are raised and etc. In whole, design of parameters of drilling and blasting operations (DBO) in deep open pit mines must take into consideration physical-mechanical and

physicotechnical properties of rocks changing with mining depth, applicable blasting explosives (BE), seismic load of bulk blasts on safety of pit walls, engineering structures and services, integrity of the ore-hosting solid and mine openings with involvement into combined open-and-underground mining of ores deposited beyond the final pit boundary near the pit edges and under the pit bottom, when the openings (adits, inclined shafts and etc.) may be driven from the exhausted area of the pit.

Meanwhile, having analyzed the current status of drilling and blasting system allowing for regularities of change in the rock solid blastability as excavation depth of Muruntau and Kalmakyr open pits increases, it has been determined that <sup>[1]</sup>:

- known methodology for calculation of blasting parameters for the rock solid in deep open pits does not fully ensure the required quality of rock breaking;
- there are no criteria of effectiveness of applicable emulsion BE using low-price components manufactured in the Republic of Uzbekistan;
- known procedures of blasting and breaking of rock mass are insufficient to increase completeness of mineral extraction;
- known DBO parameters design methods do not fully meet specified

criteria and limitations to ensure protection of the pit near-edge solid and engineering structures from seismic load of blasting;

- methodology used for calculation of parameters of safe protective pillar between open pit bottom and underground mine openings underestimates seismicity of the near zone being of great importance during concurrent open-and-underground mining of deposits;
- existing safety systems in production and application of BE with controlled energy in deep open pits do not ensure safety of operations to the full.

Thus, assessment of DBO for opencast mining of deposits up to the utmost economically expedient level shows that improvement of effectiveness of drilling and blasting system and optimization of parameters of DBO processes is feasible through:

- effectiveness of explosive breaking and displacement of rock mass;
- development of formulation with cheaper and more high-energy emulsion BE using ingredients manufactured in Uzbekistan, which characteristics suit the broken rock to the full;
- development of blasting procedures enabling to improve quality of rock mass breaking and to enhance completeness of commercial mineral extraction;

- development of efficient parameters of DBO ensuring minimization of seismic load of blasting on the near-edge solid and engineering structures;
- development of comprehensive safety system in production and use of emulsion BE with controlled energy.

## MATERIALS AND METHODS

*Determination of the basic mechanism of how parameters of blasting and physico-mechanical properties of the solid have effect on the intensity of breaking and displacement of rock masses.* The basis for solving the problem of determination of basic mechanism of how the parameters of blasting and physico-mechanical properties of the solid have effect on the intensity of breaking and displacement of rock mass is the information about extent of breaking, which is based on taking into account both physical-mechanical and mining-technological properties of rocks and ores in light of block structure and fissuring of the solid.

Experimental dependences developed for conditions of Muruntau and Kalmakyr deep open pits demonstrate that change in size of natural jointing in the rock solid with increase of depth is expressed by the following correlating equation:

$$D_i = 0.306 + 0.0036H \quad (1)$$

where  $H$  – depth of occurrence of the stratum under study (m).

Results of researches have shown that rocks of Muruntau and Kalmakyr open pits can be grouped and classified by four categories of rocks in terms of block structure and extent of fissuring: small-block, medium-block, large-block, highly-large-block rocks, coinciding with categories of blastability. Given that in calculations of DBO parameters the block structure is characterized by the average (weighted average) size of the jointing (block) in the solid, there have been developed a methodology and algorithm of calculation of size composition of broken rocks based on the economic-mathematical description of block structure of the solid and on IBWC classification. In accordance with the classification the curves have been defined, i.e. the lines delimiting the solids (massifs) of rocks of deep open pits by fissuring categories which are generally described by the equation [2]:

$$R_{iM} = 100 \cdot \exp[-3 \cdot k^2 \cdot D_i^\lambda], \% \quad (2)$$

where  $R_{iM}$  – content of blocks with size of more than  $D_i$ ;  $k$  – empirical factor characterizing the average size of the jointing  $D_{ave(s)}$  in the solid;  $\lambda$  – empirical coefficient characterizing fissuring (block structure) of the solid:

$$\lambda = \frac{0.667}{(k + 0.05) + 2} \tag{3}$$

Between the empirical factor  $k$  and average value of the jointing in the solid there is the following dependence:

$$k = \frac{0.5}{D_{ave(s)}^{1.05+D_{ave(s)}}} \tag{4}$$

Using dependences (2) (3) (4) it is possible to determine a distribution of jointings for various rocks in wide range of fissuring, particularly for Murruntau open pit with correlation coefficient  $r_c = 0.71-0.84$ :

$$\lambda = 1 + \frac{0.667}{k + 0.05}, \quad k = \frac{0.35}{D_{ave(s)}^{1.05+D_{ave(s)}}} \tag{5}$$

Given the foregoing, there has been developed an algorithm of calculation of rational elements of placing of blasthole BE charge and size composition of broken rocks. Use of the algorithm has enabled to determine a mechanism of effect of DBO parameters, physicotechnical properties of rocks and BE explosive characteristics on efficiency of breaking and displacement of rocks during blasting in deep open pit mines. At the same time, improvement of blasting efficiency and enhancement of mining safety and decrease in expenses by 7–8 % are being achieved by application of emulsion BE using inexpensive ingredients manufactured

in the Republic of Uzbekistan, which energy and detonation characteristics suit physicotechnical properties of hard rocks to the fuller extent.

There has been developed a procedure for determination of throw coefficient during rock displacement by explosion of blasthole charges under conditions of deep open pit mines depending on specific BE consumption, blasthole angle towards the sky line, stope width and bench height. As a result of statistical manipulation of pilot work findings, by this procedure the following formula for calculation of throw coefficient during displacement of rock by explosion of blasthole BE charges with correlation coefficient  $0.94 \pm 0.012$  has been derived:

$$K_{thr} = \frac{q(0.4\sin 2\alpha_c + 0.65)(0.5 - 0.016m)}{0.01\sqrt[3]{Ah + q}} \tag{6}$$

where  $\alpha_c$  - blasthole angle towards the sky line (°);  $m$  - thickness of hard seams (m);  $A$  - stope width (m);  $h$  - bench height (m);  $q$  - specific BE consumption (kg/m<sup>3</sup>).

Specific BE consumption can be regarded as an integral characteristic reflecting compressive resistance of rock and size of an average fragment (lump) of rock in a shotpile of broken rock mass. As a result of processing of

statistical data and experimental and industrial blasts the following design formula has been derived:

$$q/(\text{kg/m}^3) = (0.01 - K_a \sigma_{\text{com}} \ln d_{\text{ave}}) \quad (7)$$

where  $K_a$  – coefficient of adaptation to certain open pit conditions,  $K_a = 0.0034$  for Muruntau open pit and  $K_a = 0.0036$  for Kalmakyr open pit;  $\sigma_{\text{com}}$  – compressive resistance of rock (MPa);  $d_{\text{ave}}$  – average size of rock fragment (lump) in a shotpile (m).

Achieving the required quality of rock loosening by blasting under conditions of reducing width of blocks blasted in deep open pits solely by adjusting the specific consumption of BE is practically impossible, since spatial placing of blasthole charges have a considerable effect on results of blast. Moreover, the main initial parameter is a blasthole diameter determining the zone of controlled breaking of rocks by blasting. As a result, design formulas have been determined for a blasthole diameter and for interrelated with it other parameters of charge placing: lines of the least resistance of rock to blast, size of blasthole BE charge above the bench toe, extent of sub-drilling and uncharged part of blasthole (plug), spacing between blastholes in a row and between the rows of blastholes:

$$D = \frac{H_y C_t g \alpha + C_b}{K_f \sqrt[3]{K_e}}, \text{ m} \quad (8)$$

where  $D$  – blasthole diameter (m);  $H_y$  –

bench height (m);  $\alpha$  – bench slope ( $^\circ$ );  $C_b$  – distance between blasthole axis and bench crest (m);  $K_f$  – coefficient of adaptation of blasthole BE charge diameter to mining and technological characteristics of broken rock and conditions of charge initiation by non-electric triggering system (NTS),

$$K_f = \frac{55}{\sqrt[4]{0.1 \sigma_{\text{com}}}}, \quad K_e = K_{\text{BE}} \cdot K_{\Delta} - \text{BE}$$

relative energy concentration factor, for power industrial BE with high charging density  $K_e > 1.0$ , for reduced-power industrial BE with low charging

density  $K_e < 1.0$ ;  $\frac{Q_V}{Q_{V_0}} = K_{\text{BE}}$  – energy

conversion factor of the applied BE;  $Q_V, Q_{V_0}$  – energy of the applied BE and

the reference BE (kJ/kg);  $K_{\Delta} = \frac{\Delta_a}{\Delta_r}$

– conversion factor of charging density;  $\Delta_a, \Delta_r$  – charging density of the applied BE and the reference BE.

There have been determined changes of resistance along the bench toe during explosion of blasthole BE charge from its effective length above bench toe:

$$W/m = 0.387 e^{0.3 l_{\text{ef}}} \quad (9)$$

where  $l_{\text{ef}}$  – effective length of blasthole charge above bench toe (m).

Adjustment of spatial arrangement of blasthole charges with specific BE

consumption is made by alignment of spacing between blastholes that at  $a = b$  is determined by the formula:

$$a_d = \sqrt{\frac{Q}{qH_y}}, \text{m} \quad (10)$$

where  $a_d$  – adjusted spacing between blastholes (m);  $Q$  – BE weight in blasthole (kg).

Blasting operations conducted in Murantau deep open pit in accordance with the developed procedure in view of changing physico-mechanical properties of the solid with increase in the pit excavation depth have shown even-er breaking of the solid at reducing BE costs by 12 %.

*Substantiation of DBO parameters using emulsion BE providing improvement of effectiveness and safety of blasting operations.* Due to the fact that in Murantau and Kalmakyr open pits only in-house produced blasting explosives are being used, all regulations, normative documents and analytical dependences characterizing design values of specific BE consumption and DBO parameters have been amended so as to take into consideration relative explosive force of the applied BE in relation to the reference BE (Grammonit 79/21), which analysis has shown that at emulsion BE efficiency factors equal to 1.05 (Nobelit 2030) and 1.07 (Nobelan 2080) the charge column length in

a blasthole shortens by 32 % and 27 %, specific energy consumption decreases by 26–30 %. In this regard, abatement of extent of effective utilization of explosive energy of blasthole charge for breaking and expansion of zone of uncontrolled breaking is apparent. For the purpose of neutralizing these negative factors it has been proposed to compensate the shortening of charge column length by using a combination of blasthole emulsion BE charge +ANFO and by inverse initiation by blasthole detonator of non-electric triggering system (NTS), during which the primary pre-breaking of the solid mass is done by high brisant emulsion BE, and final phase of breaking - by low brisant BE, i.e. by ANFO. In such case, later ignition of ANFO locks up explosion products thus extending their duration in charge chamber and accordingly facilitating the improvement of effective utilization of explosion energy for breaking and working of bench toe. Pilot works have recorded that application of combined charge structure improves its explosive force as compared to single charge structure by 15 %, at the same time displacement of ore boundary and host rock decreases as much as 1.5–2.0 times, rock breaking quality improves with simultaneous reduction of BE costs by 20 %.

For the purpose of improvement of EBE and WEBE application efficiency and reduction of cost price of explo-

sive rupture of rocks in deep open-pit mines, researches have been made to improve formulation of matrix emulsion and emulsification process of feedstock solutions aimed at possibility to use inexpensive raw ingredients made in Uzbekistan. Assessment of emulsion physical stability using various samples of emulsifiers has demonstrated that cost of ingredients, their market availability and acceptance analytical test of raw ingredients or manufacturers' guarantee of conformity with quality standards and technical requirements of process procedure must be the criteria for selection of ingredients for oil fraction used for production of emulsion at the EBE plant.

With the view of reducing expenditures for purchase of raw ingredients and expendable materials some researches have been conducted to optimize formulation and manufacturing method of emulsion explosive formulations (EEF) which made it possible to reduce percentage of imported raw ingredients from 5.2 % to 4.5–4.0 % and to modernize equipment and instrumentation in manufacturing scheme of the EBE plant, thus enhancing efficiency and safety of EBE production.

As for priorities for further work on improvement of formulation for EBE production, there have been offered EEF where calcium nitrate is used to increase explosion energy, and car-

bamide inhibiting interaction of EEF and sulphide rock is added into oxidants solution, in case of lack of sulphides in rock it can be replaced with ammonium nitrate. It is recommended to avoid application of wax, paraffin, acetic acid, sodium nitrite, sodium lye solution, thiourea, Swedish porous nitre which should be replaced with petrolatum, microspheres or foamed polystyrene. According to economic estimation, the EBE produced by the recommended formulation costs by 10–25 % less as compared to similar energy characteristics. Cost of 1 t of matrix in terms of raw ingredients is reduced by USD 130 for machine-aided charging and by USD 78–96 for cartridge EBE. For improvement of efficiency and safety of EBE production the sections such as liquid ammonium nitrate intake section, cartridge cooling section, oil solution makeup section and etc. have been modernized and reconstructed based on performed pilot works.

As a result of research works the DBO parameters have been determined to provide optimal placement of EBE charge in the solid mass, basic values of blasthole network size depending on used drilling tool and potential of their applicability. Thus, for hard-to-blast ore zones in Muruntau open pit: the network size of 6.0 m × 6.0 m is for 250 mm diameter blastholes; specific BE consumption in dry blastholes



is 1.10–1.25 kg/m<sup>3</sup> (Nobelan 2080), in watered blastholes it is 1.15–1.30 kg/m<sup>3</sup> (Nobilit 2030); stemming space length is 5–6 m. In the rock area of the open pit mine it is possible to apply the 250 mm diam. blasthole network having size of 6.5 m × 6.5 m at specific BE consumption of 0.98–1.05 kg/m<sup>3</sup> and stemming space length of 5.5–6.5 m. The developed parameters of DBO adapted to EBE have enabled to reduce expenditures for blasting by 15 % with the best handling of the rock solid along the whole height of the blasted bench.

*Development of effective blasting techniques enabling to improve quality of rock mass breaking and to enhance completeness of extraction of commercial mineral.* Intensification of geomechanical effects with increasing mining depth has impact on achieving the target quality of breaking. This imposes further requirements to explosive rupture of rock which are implemented by means of new methods and parameters.

Researches on quality of rock mass breaking have demonstrated that even observing the determined optimal parameters of charge placing in the solid and at increased specific EBE consumption ( $q$ ): on average for Nobelan 1.11 kg/m<sup>3</sup> (maximum value is 1.27 kg/m<sup>3</sup>); and for Nobelit 1.26 kg/m<sup>3</sup> (maximum value is 1.59 kg/m<sup>3</sup>) it is impossible to avoid yield of oversize

and coarse size. Moreover, at  $q \geq 1.15$ –1.20 kg/m<sup>3</sup> as a result of predominance of throwing (propellant) effect of an explosion over rending effect a considerable portion of rock mass is thrown from the side of mined-out area (10–20 %) on lower horizons or formation of shotpiles as wide as up to 40 m takes place. In the first case this results in decrease of quality and amount of ore, and in the second case this causes drop in intensity of mining operations.

In this regard, researches have been conducted to increase duration of explosion effect on the upper part of bench and to enhance stemming efficiency. Specifically, to increase duration of explosion effect on the solid mass and to enhance locking effect it is recommended to use dynamic stemming consisting in explosion of BE charge in an additional short blasthole drilled at 2 m distance off the main blasthole or explosion of locking charge in stemming space of the main blasthole. NTS was used to initiate BE charges: in blastholes by nonelectric explosion initiating device-B (blasthole) with delay of 500 ms; the surface network was arranged by nonelectric explosion initiating device-S (surface) with delays of (25, 42 and 67) ms. On experimental areas the delays were selected in such a manner that the locking charge was the first to explode and then the main (primary) charge exploded. Retardation of the main

charge relative to locking charge with placing the latter in the main blasthole was maintained by various length of shock-wave tubes (SWT) for lower and upper boosters with their concurrent initiating by detonator of surface network and was about 7 ms at 2000 m/s detonation speed in SWT. In order to delay the primary charge relative to locking charge in additional blasthole a combination of retardants rating (25, 42 and 67) ms in surface network was used. As a result, an interval between explosion of the primary charge and locking charge was between 17–25 ms. It has been established that application of locking charge in additional blasthole has increased extent of rock solid breaking by 8–10 % and reduced specific BE consumption by 3 %.

Application of emulsion explosive formulations (EEF) with controlled volume concentration of explosion energy applicable for charging dry and watered blastholes, together with combined structure of charges makes it possible to meet in practice any technological challenges of DBO owing to available park of drilling rigs. This circumstance promotes increasing height of benches that allows of reducing quantity and length of transport horizons, increasing open pit wall slope, enhancing intensity of mining in deep open pits. Moreover, engineering and economical performance of open pit mining is increasing.

A procedure of high bench blasting has been developed, which main point consist in the following. Rocks are broken by a pair of divergent blasthole charges. Specifically, one blasthole in each pair is drilled perpendicularly to bench toe, and the second one – towards bench slope with incline to the toe. Vertical and inclined blastholes are arranged in parallel vertical planes spaced apart by distance equal to 1–2 diameters of blasthole equivalent in terms of charge energy to total charge in a pair of divergent blastholes. Blasthole angle and limit bench height are determined by the following formulas:

$$\beta = \arctg \frac{1.13H}{d_e} \sqrt{\frac{q}{\gamma}}, \text{ degree};$$

$$H = \frac{2d_e \sqrt{\frac{\pi \cdot \gamma}{q} - 2c}}{2 \cdot \text{ctg} \alpha}, \text{ m}$$
(11)

where  $\alpha, \beta$  – angles of bench slope and inclination of blastholes in cluster;  $H$  – bench height;  $d_e$  – diameter of charge equivalent in terms of charge energy to total charge in a cluster of blastholes;  $q$  – specific BE consumption;  $\gamma$  – density of charging BE in a blasthole;  $c$  – safety berm.

Effectiveness of the developed procedure of high bench blasting has been tested experimentally during re-activation of western wall of Muruntau open pit mine. An area of the pit

wall to be blasted included four 15 m benches, which were combined in two 30 m benches during the experiment. Diameter of blastholes was 250 mm. Blastholes network was 7 m × 7 m. Specific BE consumption was 0.95 kg/m<sup>3</sup>. Charge structure was combined (EBE and ANFO). In a pair of divergent blastholes the BE charge was placed in vertical and inclined ( $\beta = 65^\circ$ ) blastholes.

Study of size composition of the blasted rock mass by photo-planimetric method has shown that average size of fragments of rock mass does not exceed 22–25 cm (under similar conditions on benches of 15 m height it was 27–30 cm.)

A wide range of changing mining-and-geological properties of rocks in deep open pits requires an individual approach during blasting of rocks with different bastards occurred in less hard hosting rocks. When blasting the solid with hard interlayers on narrow operating benches in a large deep open pit it is necessary to ensure their proper blasting and formation of compact shotpile that is uniform by fractional composition. This can be achieved by placing BE in areas of occurrence of bastards or by increasing duration of explosion effect. These two approaches are combined in the developed technology of blasthole BE air-cushioned charge with concavity in bottom part of the

charge. In order to raise the charge to the level of bastards, in the bottom part of the blasthole an air cushion of 1–2 m length is formed, and to blast the lower part of the solid a concavity is made in the bottom part of BE charge. BE charge is initiated at height of 2/3–3/4 of the charge length. An air gap made with concavity forms a jet which creates a chock wave directed downwards and sideways off a blasthole. In turn, stress waves from cumulative (cavity) charge directed upwards produce secondary breaking (fragmentation) of upper rock. Directing energy of a part of a BE charge towards bottom of blasthole increases duration of explosion effect on the solid and forms two stress waves having impact on the whole solid. Conducted researches based on physical simulation and pilot blasting have established that more efficient placement of BE charge is at the depth off the bastard up to 1/2 its thickness, at the seam thickness of 1.5 m; and at 1/3 its thickness at the seam thickness of less than 1/4 bench; immediately under the seam or partially in the seam at the seam thickness of more than 1/4 bench height.

A blasting procedure for rocks with different bastards has been developed, as a result of which the effectiveness of breaking different bastards (hard inclusions) has increased due to taking into consideration the main properties of hosting rocks, bastards and used BE

and is achieved by drilling additional blastholes to main holes inside bastard contour with placing BE charges in them inside bastards. Selection of BE for charging additional blastholes is made by value of BE detonation velocity determined by the following correlation:

$$D_{\delta} = D_0 \sqrt{2 \frac{\sigma_t^{bast}}{\sigma_t^{hr}} - 2 \sqrt{\frac{\sigma_t^{bast}}{\sigma_t^{hr}}} + 1} \quad (12)$$

where  $D_{\delta}$  – BE detonation velocity for charging additional blastholes (m/s);  $D_0$  – BE detonation velocity for charging main blastholes (m/s);  $\sigma_t^{bast}$  – ultimate tensile strength of bastard rock (Pa);  $\sigma_t^{hr}$  – ultimate tensile strength of hosting rock (Pa).

Additional blastholes are drilled to the depth of:

$$l_{\delta} = \frac{\sum_{i=1}^n l_{on_i}}{n} - (1.5 \dots 5.0) d_{adhole_{\delta}}, \text{ m} \quad (13)$$

where  $l_{on_i}$  – mark of bastard bottom by depth of main blastholes, between which a respective additional blasthole is arranged (m);  $n$  – number of main blastholes, between which a respective additional blasthole is arranged;  $d_{adhole_{\delta}}$  – diameter of additional blastholes (m).

Both incomplete drilling of additional blastholes up to bastard bottom to length of 1.5–5 diameters of blastholes

and incomplete charging to the same length up to bastard ceiling eliminates orientation of explosion action towards hosting rock having lesser resistibility to blasting.

Experimental blasting of rock in Murantau open pit by bastards using the developed technology of blasthole BE air-cushioned charge with concavity in its bottom part and method of blasting of rocks with different bastards have shown effectiveness of the solid breaking with formation of compact and uniform by fractional composition shotpile with decreasing specific consumption of BE by 7–8 %.

*Determination of blasting operations parameters providing safety of the near-wall solid and engineering structures from seismic load of blasting.* It is known that during blast loosening of rock there are seismic waves of huge intensity having impact on safety of the near-wall solid and engineering structures [3].

Generally accepted criterion of estimation of blast seismic effect is medium displacement velocity (U):

$$U = K[\sqrt[3]{Q/R}]^n \quad (14)$$

where  $K$  – soil conditions coefficient;  $n$  – factor of extent of seismic wave attenuation characterized by the dependency:  $n = 2 - \frac{\mu}{1 - \mu}$ ;  $\mu$  – Poisson ratio.

Safety of the near-wall solid and engineering structures will be ensured if deformations of the wall solid and foundations of protected structures caused by explosion effect do not extend the limits of horizontal component of vibration velocity  $U_{adm.} \geq U_x$ , whose dependence on horizontal distance off the blast point ( $R$ ) is described by the equality  $U_x/(cm/s) = 450 \cdot R^{-1.85}$ , and the estimate of tolerable vibration velocity will be:

$$\sigma_{adm.} = \rho \cdot C_p \cdot U_{adm.} \quad (15)$$

where  $\sigma_{adm.}$  - stress at which a sample of the open pit rock is not ruptured by multiple dynamic impacts;  $\rho$  - average rock density;  $C_p$  - mean value of velocity of medium displacement along the horizontal component on longitudinal wave front;  $U_{adm.}$  - mass velocity of the solid vibrations (displacements) taken as admissible criterion of an estimate of seismic explosion wave impact on the solid.

Having set values of distance between blast point and protected object it is possible to determine seismically safe weight of charges for instant detonations. In addition, to avoid interferences of seismic waves it is required that delay intervals ( $t_3$ ) exceed lifetime of plus phase of seismic waves:

$$t_3 \geq K_t \cdot \lg R, c \quad (16)$$

where:  $K_t$  - coefficient allowing for rock hardness,  $K_t = 0.01-0.03$ .

A seismically safe for adjacent protected objects method of rock blasting without decreasing rock breaking effect has been recommended. As an example let's consider an implementation of seismically safe technology for conducting DBO in Muruntau open pit, where a task of prevention of destruction of five objects located on the pit wall at the distance of 120 m; 750 m; 720 m; 480 m; 80 m off centre of the blast block was solved. For this purpose, a block to be blasted has been chosen on horizon +375 m and a project for conducting the DBO within the zone of adjacent objects with achieving the design performance of seismic loads in different directions off the centre of the blasted block has been plotted graphically on computer. The block to be blasted is prolate shaped with narrowed ends characterized by two parameters - length and width. Given that the block to be blasted is surrounded by several protected objects, a distance  $R_i$  ( $i = 1 \dots n$ ) to protected objects is measured by connecting centre of the block to be blasted with protected objects. Amongst  $R_i$  distances the shortest one is chosen. The prolate shaped block is oriented with the long side in the line of the nearest protected object  $R_{min}$  (Figure 1).

After the drilled block has been oriented accordingly, rows of blastholes in plan view are inclined at an angle within the range from  $45^\circ$  to  $135^\circ$  to



where  $R_1 = 120$  m;  $R_2 = 750$  m;  $R_3 = 720$  m;  $R_4 = 480$  m,  $R_{min} = 80$  m: blasted block-protected objects distance; Перегрузочный пункт - Dumping station; Борт карьера - Pit wall; КНК-270 – High-angle conveyor-270; ЦПТ – Cyclic-and-continuous process; ДПП – Crushing-and-conveying plant

**Figure 1.** Orientation of an area of the blasted block relative to some protected objects

**Table 1.** Results of mathematical modeling of seismic load on protected objects of the open pit

Configuration of blasted block	Seismic load rate					Extent of stability of an object				
	$R_1$	$R_2$	$R_3$	$R_4$	$R_{min}$	$R_1$	$R_2$	$R_3$	$R_4$	$R_{min}$
Trapeze	37.1	21.8	20.7	29.2	37.8	–	+	+	+	–
Rhomboid ( $\alpha = 90^\circ$ )	20.5	12.9	16.1	18.9	26.4	+	+	+	+	+
Rhomboid ( $\alpha = 120^\circ$ )	18.3	10.5	14.2	16.4	24.1	+	+	+	+	+

the bee-line (the shortest distance) to the object. Wiring-up of the explosive circuit is made so that it could lead to successive detonation of charges in the direction from the chosen protected object to centre of the blasted block.

Arrangement of blastholes on the chosen block within the prolate-shaped area oriented in plan view with nar-

rowed ends along the bee-line to the chosen protected object enables, due to optimal shape of the area and angles of inclination of blasthole rows in the range of  $45\text{--}135^\circ$ , to achieve redistribution of released seismic energy by width and length of explosion field.

Calculated by mathematical modeling rates of seismic load and findings on

objects safety in case of trapeze- and rhomboid-shaped blast block at an angle of blasthole rows inclination  $\alpha = 90^\circ$ ,  $\alpha = 120^\circ$  are presented in Table 1.

The analysis of the findings shows that when a trapeze configured block is blasted, three protected objects stand seismic load and two are destroyed, and when an elongated rhomb configured block is blasted, the whole group of protected objects stand seismic load.

It has been established that blasting method, including drilling of blasthole rows in a block of definite configuration, their charging and short-delayed blasting, in which case the blastholes rows are commuted in a block having an elongated configuration view in plan with narrowed opposite ends at an angle of  $45^\circ \leq \alpha \leq 135^\circ$  to a beeline to one of the chosen protected objects, provides reducing seismic load on protected objects:

- in the direction of commencement of blasting the rows – twice;
- to the left and to the right of the explosion field in  $120^\circ$  sectors - four times.

Successive detonation of blasthole rows with delay from the nearest hole in the direction from the protected object results in redistribution of released seismic energy in such a manner that the maximum flow of seismic energy is directed towards the side oppo-

site to the protected object. This fact has been determined experimentally. When length of rows in the blasthole block is reduced, a number of blasthole rows are increased to maintain the total target weight of blasted BE and a total number of rows, that leads to decrease in extent of seismic load and concurrent increase in seismic load duration. The two said factors allow of adjusting flow of seismic energy on protected group of objects so that the shock effect on the nearest object could be minimal and the other nearby objects could be practically safe.

Using the open pit space for mining of ore deposits outside the pit contour enables to implement advantages of combined open-and-underground mining method to the full. At the same time, conventional approach to design and operation of deep open pits does not take into consideration changing mining methods in view of development of underground mine. In this regard, researches have been conducted to determine safe parameters of arch pillar separating open and underground mining operations. In calculations it is deemed that rock is the elastoplastic solid medium. To ensure stability of the arch pillar solid it is required that seismic load does not cause irreversible deformations. The condition of maintenance of rock stability is written as follows:

$$U \leq U_0 \quad (17)$$

where  $U$  – velocity of rock displacement caused by explosion (cm/s);  $U_0$  – safe velocity of rock displacement based on conditions of their elastic deformation (cm/s).

Velocity of rock displacement  $U$  depending on charge size, distances to protected object and elastic impedance of rock can be expressed by the following formula:

$$U = \frac{3.72 \cdot 10^6 \cdot Q^{0.4}}{R^{1.75} \cdot \sqrt{C_p \cdot \rho}} \quad (18)$$

where  $Q$  – weight of simultaneously blasted charge (kg);  $R$  – distance to protected object (m);  $C_p \cdot \rho$  – elastic impedance of rock (m/s · kg/m<sup>3</sup>).

Safe velocity of rock displacement can be determined from general conditions of their deformation. If in the course of deformation of volume  $V_0$  to volume  $V_1$  the specific energy of volume  $V_0$  increases by some final and quite definite for certain medium value  $F$ , this forms necessary and sufficient conditions for rupture. Then, general equation of energy conditions defining potential rupture of medium can be presented as follows:

$$\frac{W_1}{V_1} - \frac{W_0}{V_0} \geq F \quad (19)$$

where  $W_0$  and  $W_1$  – energy of medium before and after rupture (kg m);  $V_0$  and  $V_1$  – volume of medium before and after rupture (m<sup>3</sup>).

Rupture (breaking) stress can be defined as follows:

$$\sigma_p = -\frac{3}{8} \cdot K \left[ \left( \frac{V_0}{V_1} \right)^{4/3} - \left( \frac{V_0}{V_1} \right)^4 \right] \quad (20)$$

where  $K$  – coefficient depending on properties of massif.

Stress on elementary surface inside the rigid body acts on both normal and tangent. The body referred to three perpendicular axes  $Q_x, Q_y, Q_z$  is affected by at least three stress components  $\sigma_1, \sigma_2, \sigma_3$  causing 6 more components  $\sigma_{xy}, \sigma_{yz}, \sigma_{xz}, \sigma_{yx}$  and etc. Action of these very components of stress causes deformation of volume  $V_0$  to  $V_1$  during its change from  $\rho_0$  to  $\rho_1$ .

Given that  $\frac{\sigma_1 + \sigma_2 + \sigma_3}{E}$  in whole defines volumetric strain (relative volume deformation) ( $\varepsilon$ ) of the medium under action of total stress tensor ( $\sigma_1, \sigma_2, \sigma_3$ ), we obtain:

$$\sigma_p = -\frac{3}{8} \cdot K \cdot \frac{\left\{ [1 + (1 - 2\mu) \cdot \varepsilon]^{8/3} - 1 \right\}}{[1 + (1 - 2\mu) \cdot \varepsilon]^4} \quad (21)$$

where  $E$  – dynamic modulus of elasticity;  $\sigma_1, \sigma_2, \sigma_3$  – total stress tensor; negative values of  $\sigma_p$  conform to compression stress as in this case deformations are positive, and positive values of  $\sigma_p$  conform to tensile stress as deformations are negative here.



Use of dependence (21) is of great importance for practice as besides general qualitative dependences in determination of parameters of rupture

process, we take into account the effective (working) stress  $\sigma_p$  related to the known dependence from theory of elasticity:

$$\sigma = \frac{U \cdot C_p \rho}{q} \tag{22}$$

that enables to determine safe velocity of rock displacement  $U_o$ :

$$U_o = \frac{12,5 \cdot C_p \cdot \left\{ [1 + (1 - 2\mu) \cdot \varepsilon_o]^{8/3} - 1 \right\} \cdot (1 + \mu)}{[1 + (1 - 2\mu) \cdot \varepsilon_o]^4 \cdot (1 - \mu)} \tag{23}$$

where  $C_p$  – velocity of P-wave propagation (m/s),  $C_p = 4000$  cm/s;  $\mu$  - Poisson ratio,  $\mu = 0.25-0.30$ ;  $\varepsilon_o$  – admissible relative deformation of rocks within elasticity, for conditions of the mine horizons +128 m, +78 m and  $\pm 0$  value  $\varepsilon_o$  is accepted within the range of 0.0003–0.0004.

Subject to dependences (17), (18) and (23) we derive an equation for determination of required thickness of protective pillar over underground mine workings at different values of BE charge weight ( $Q$ ) per one retardation:

$$R = \frac{1380 \cdot Q^{0.228} \cdot [1 + (1 - 2\mu) \cdot \varepsilon_o]^{2.28}}{C_p^{0.856} \rho^{0.286} \left\{ [1 + (1 - 2\mu) \cdot \varepsilon_o]^{8/3} - 1 \right\}^{0.57}} \cdot \left( \frac{1 - \mu}{1 + \mu} \right)^{0.57} \tag{24}$$

Results of calculation of ceiling thickness, pillar (protected pillar) are determined subject to seismic explosion effect of bulk blasting conducted in the open pit based on BE charge weight per one retardation and are 50 m for Muruntau open pit (Figure 2).

deformation of rock within the elasticity limits in accordance with classification of protective structures by their responsibility and lifetime.

*Development of comprehensive safety system in production and use of blasting explosives in deep open pit mines.*

Researches have been made on seismic load of huge blasting to determine critically admissible deformations and velocities of displacements for surface engineering structures and underground mine workings. It is recommended to set an admissible relative

It is known that main technological and operational properties of emulsion BE (EBE) depend on correct selection of formulation of oxidant, emulsifier, method of emulsion production, nature of sensibilizing additive and EBE manufacturing equipment.

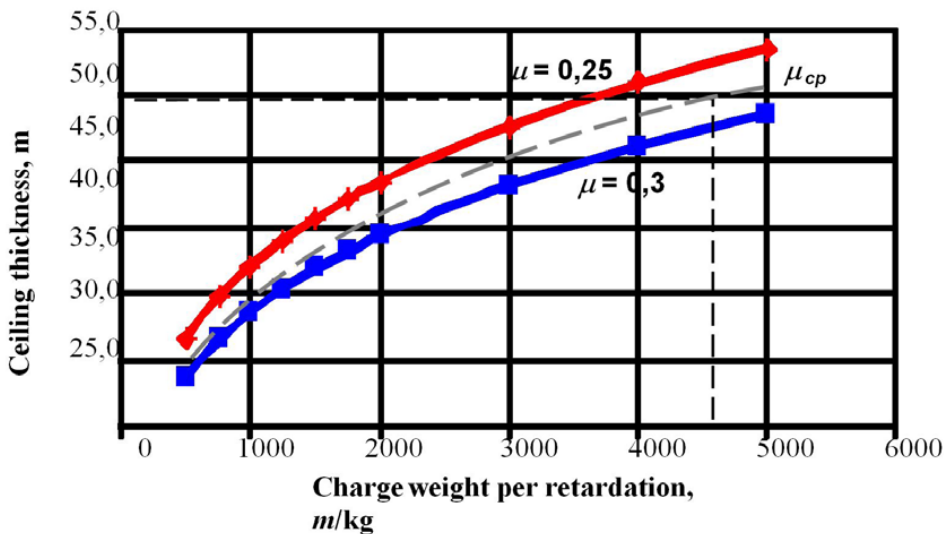
It has been established that having a number of advantages over other types of industrial BE, EBE composition has some specific features: there is a number of critical parameters of external effects, which increasing leads to generation of initial site (of explosion); EBE decomposition runs at molecular level and requires no additional reagents; EBE is characterized by high energy concentration and velocity of energy output, which, as a rule, ends in explosion having effect on the environment (equipment, buildings and structures, personnel). Therefore, production and use of EBE require strict regulation as per safety requirements [4].

Level of average technical (theoretical) risk for EBE manufacturing plant has

been calculated as a sum of criteria of probability (theoretical frequency) of occurrence ( $B$ ) and importance of consequences of undesirable events ( $P$ ) in terms of more serious events ( $n$ ). The risk level was:

$$\frac{\Sigma(B_n + P_n)}{n} = 6,5 \text{ points.} \quad (25)$$

Based on results of the assessment it can be concluded that the total risk level during operation of EBE plant under current conditions is acceptable like for a hazardous industrial object subject to observance of technical and organizational measures (safety system) aimed at risk mitigation. And at the same time, a source of uncertainty of risk assessment is the human factor and equipment failure.



**Figure 2.** Ceiling thickness changing from the level of seismic explosion effect for conditions of Muruntau open pit

Based on researches and analysis of risk level of EBE plant for the purpose of unconditional provision of safe production of EBE a comprehensive safety system has been developed for safe operation of the EBE plant (Figure 3).

In addition to the active (instrumentation) safety system existing at the EBE plant, in order to maintain safe and steady operation of processing equipment, it has been recommended to in-

clude into the modernization program the following elements: backup emergency stop push button in operator's room; staff evacuation audio signal (alarm sirens and beacons) at actuation of emergency shutdown of operation; reducing maximum temperature settings on mixers and pumps from 150 °C to 140 °C; additional installation of protective systems on Netzsch stators; Ametist IP type 329-5 01 "Flame Announcer" sensors respond-

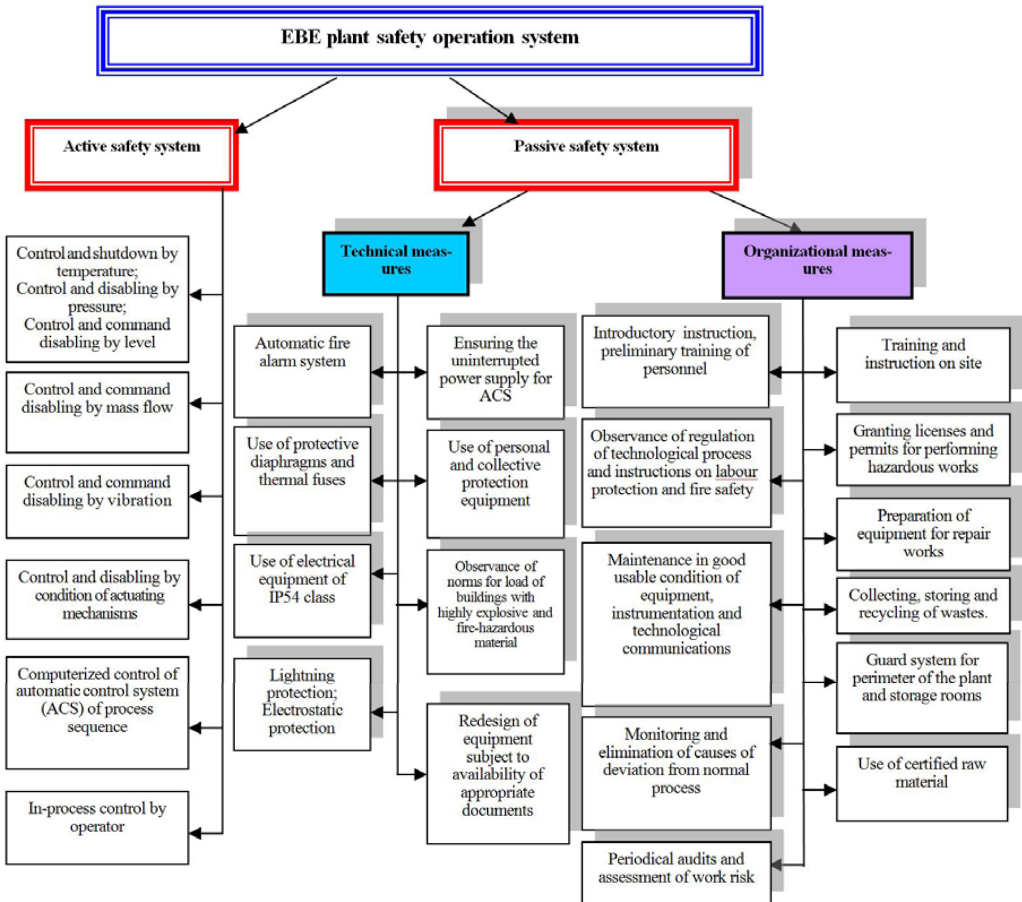


Figure 3. Recommended comprehensive safety operation system of the EBE plant

ing to open flame emergence with outputting the signal from sensors to staff evacuation audio signal (alarm sirens and beacons) should be installed in rooms for preparation of oxidizing and oil solutions, packaging, packing and cartridging equipment in addition to fire-control warning system. The developed comprehensive safety operation system made it possible to ensure safe production of EBE at the plant and accordingly reduce the existing risk level of the plant from 6.9 points to 4.0 points.

In view of the fact that parameters of formula for calculation of range of rock movement during explosion of blasthole charges at open mining operations, as set forth in effective "Unified Safety Regulations For Blasting Operations" of 1992 edition, are relative and nondimensional values, substantiation of predictive assessment of blasting operation conducted in proximity to mining equipment and engineering facilities under conditions of deep open pits in terms of damaging action of the blasted rock fragments has been conducted:

$$R_0 = R_{\text{MOV}} \times K_{\text{STEM}} + \Delta R \quad (33)$$

where  $R_0$  – maximum range of rock movement;  $R_{\text{MOV}}$  – predictive assessment of maximum range of rock movement;  $K_{\text{STEM}}$  – coefficient of stemming value influence on range of rock movement,  $K_{\text{STEM}} = 1/(0.8 + 0.002 L_{\text{STEM}}^{-1.8})$ ;  $L_{\text{STEM}}^{-1.8}$  – length of stemming expressed

in diameters of blasthole charge,  $\Delta R$  – wind drift of blasted rock fragments to leeward side,  $\Delta R = 5 V$ ;  $V$  – wind velocity (m/s).

Comparative calculation of maximum range of blasted rock movement demonstrates that range of rock movement as per the developed methodology subject to use of stemming and wind drift is lower respectively by 71.5 m and 46.5 m. Change in routine of bulk blasting in Muruntau deep open pit has made it possible to enhance effectiveness and safety of blasting operations, to reduce downtime of mining transport equipment and annual expenditures for blasting operations by USD 105 thousand.

## CONCLUSION

Thus, there have been determined theoretical generalization and solution of scientific problem of determination of regularities of explosive rupture and substantiation of DBO efficient parameters suitable for the rock to be broken in deep open pits that is of great economic importance and ensures reducing expenditures for blasting operations, increasing their effectiveness subject to application of EBE with controlled energy using inexpensive ingredients manufactured in the Republic of Uzbekistan, minimization of seismic load of blasting on the

near-wall rock solid and engineering structures, improvement of breaking quality and completeness of extraction of commercial minerals from the earth. A strategy of effective development of blasting operations has been developed for mining enterprises that is aimed at enhancement of safety level of blasting operations, technology of EBE production and blastholes charging.

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## Geophysical and sedimentological studies for reservoir characterization of some tar sands deposits in southwest Nigeria

### Geofizikalne in sedimentološke preiskave za opredelitev rezervoarnih lastnosti nekaterih nahajališč naftnega peska v jugozahodni Nigeriji

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**Abstract:** Electrical resistivity tomography for 2-d subsurface imaging has been integrated with sedimentological and petrophysical analyses for detailed mapping and reservoir characterization of some Nigerian tar sands deposits in southwestern Nigeria with a view to generate a spatial distribution and reservoir quality description as well as compare the result with already characterized deposits in other parts of the Nigeria tar sands belt.

Electrical resistivity survey delineated a relatively thick (average thickness of 50 m) high resistivity tar impregnated sand layer with resistivity value range of 1519  $\Omega$  m to 5772  $\Omega$  m, which is located about 10 m below the ground surface. Granulometric analyses of eight samples of the tar sands deposit indicate fairly well distributed reservoir sand with grain size distribution range between  $\phi$  = 0.03–0.55 mm with up to 3 % fines. The reservoir sands is poor to moderately well sorted ( $\phi$  = 0.94–1.63 mm), the measure of skewness indicates a strongly coarse to strongly fine skewed (–0.–0.47) reservoir sands. Petrophysical analyses such as porosity and permeability range from 16–24 % and 143–887 mD, respectively. The tar sands deposit was also analyzed to have between 60–90 % hydrocarbon impregnation, while bitumen saturation of the mass fractions 18–30 % was recorded. The viscosity of the impregnated

heavy oil with API gravity less than 20° and a specific gravity value range of 0.95 g/cm<sup>3</sup> to 1.27 g/cm<sup>3</sup> was determined to range between 1.080 Pa s to 1.360 Pa s. The results obtained agreed with borehole information and earlier published geophysical and petrophysical results of the tar sands deposits located in other parts of the Nigerian tar sands belt.

**Izvešček:** Električna upornostna tomografija s podzemnim 2-d-prikazom v povezavi s sedimentološkimi in petrofizikalnimi analizami je bila uporabljena za detajlno kartiranje in rezervoarno opredelitev nekaterih nahajališč naftnih peskov v jugozahodni Nigeriji z namenom ugotoviti prostorski razpored, opredeliti rezervoarne lastnosti in izvesti primerjavo z že raziskanimi nahajališči v drugih delih nigerijskega pasu naftnih peskov.

Z električno upornostjo je bilo mogoče omejiti razmeroma debelo (povprečne debeline 50 m) visoko uporno (v razponu 1519–5772 Ω m) plast peska, prepojenega z bitumnom in ležečega okoli 10 m pod površjem. Granulometrična preiskava osmih vzorcev iz nahajališča naftnega peska nakazuje razmeroma enakomerno porazdelitev rezervoarnega peska z zrnovitostjo med  $\phi = 0,03$  mm in 0,55 mm in z do 3 % fine frakcije. Rezervoarni pesek je slabo do srednje dobro sortiran ( $\phi = 0,94$ –1,63 mm), ugotovljena asimetričnost pa nakazuje zelo debelozrnato do zelo drobnozrnato asimetrične (–0,58 to 0,47) rezervoarne peske. Rezultati preiskave poroznosti in prepustnosti so v razponih od 16 % do 24 % in ustrezno 143 mD do 887 mD. Stopnja impregniranosti z ogljikovodiki se giblje med 60 % in 90 % in stopnja nasičenosti z bitumnom med masnima deležima 18 % in 30 %. Viskoznost impregnirane težke nafte, ki ima relativno gostoto pod 20° API in specifično maso med 0,95 g/cm<sup>3</sup> in 1,27 g/cm<sup>3</sup>, se giblje med 1,080 Pa s in 1,360 Pa s. Dobljeni rezultati ustrezajo meritvam v vrtnah in objavljenim geofizikalnim in petrofizikalnim podatkom z nahajališč peskov v drugih območjih nigerijskega pasu naftnih peskov.

**Key words:** tomography, reservoir characterization, tar sands, porosity, permeability

**Ključne besede:** tomografija, rezervoarna opredelitev, naftni peski, poroznost, prepustnost



## INTRODUCTION

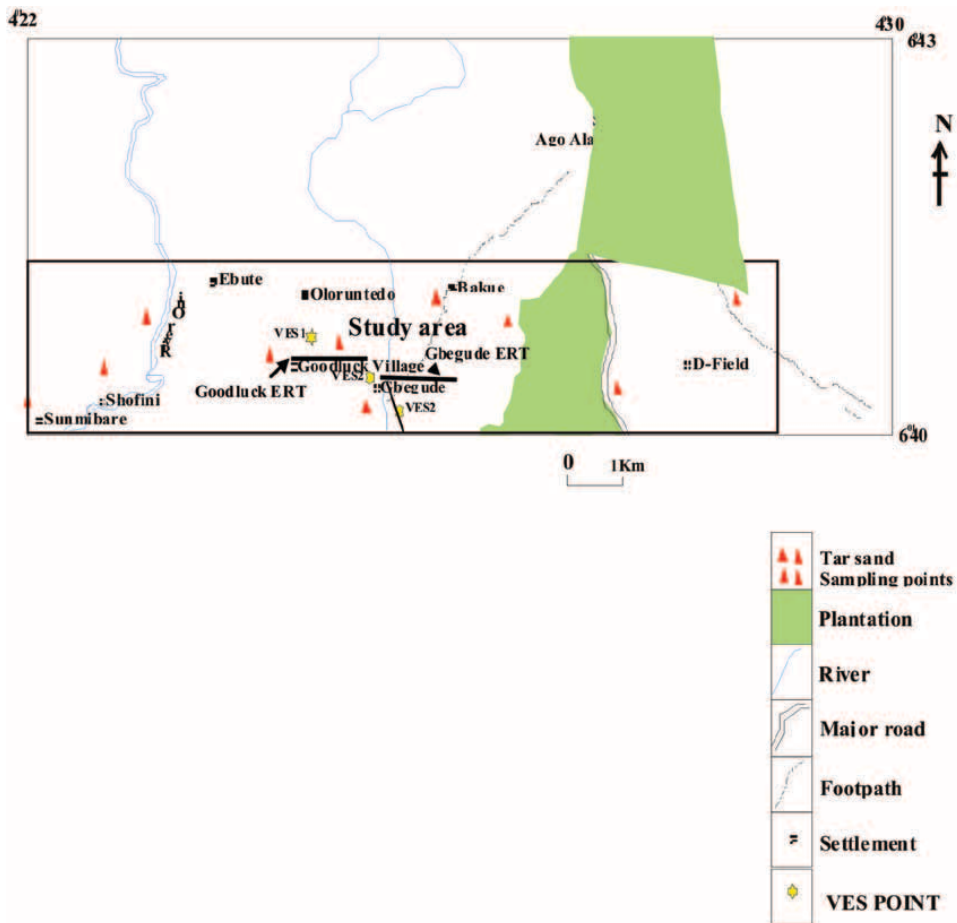
Asphalt-impregnated sandstones otherwise referred to as oil sands (tar sands) and active oil-seepages occur in southwestern Nigeria within the marginal pull-apart or margin-sag Dahomey (Benin) basin. The oil sands outcrop in an E-W belt, approximately 140 km long and 4–6 km wide, extending from Edo, Ondo and Ogun State in southwest Nigeria. Bituminous sands are composed of sand, heavy oil and clay that are rich in minerals and water. The heavy oil in the bituminous sand is commonly called bitumen, which is a very dark coloured, sticky and viscous substance. Total reserve of the heavy oil is estimated to exceed 30 billion barrels (ADEGOKE et al, 1980).

The petroleum habitat is almost exclusively the Afowo Formation, a member of the Abeokuta Group. This litho-unit is of Turonian - Maastrichtian age and consists of interbeds of coarse-medium grained sandstones, siltstones and shale deposited in a transitional to marginal marine environment (OMATSOLA & ADEGOKE, 1981). The oil is found in the coarse grained clastics within the formation in two discrete bands (the X and Y horizons), each 30–40 m thick and separated by 6–15 m carbonaceous shales with a thin band of lignite (AKO et al., 1983) and overburden thickness in excess of 50 m at Agbabu, Ondo State, south western Nigeria (ENU, 1985).

This research utilizes electrical resistivity studies, sedimentological and petrophysical studies to characterize the reservoir sands of the tar sand deposits in Gbegude area; a continuum of the tar sand belt of North-Eastern Dahomey basin, South Western Nigeria. The study is aimed at delineating the subsurface distribution and occurrence of the deposits as well as determining the reservoir characteristics of the tar sand deposits in the study area.

## GEOLOGICAL SETTING

The study area is situated in the eastern part of Dahomey basin and located within longitude 4°22'E to 4° 30'E and latitude 6° 40' N to 6° 43' N (Figure 1). The Dahomey Basin constitutes part of the system of West African pericratonic (margin sag) basin (KLEMMER 1975; KINGSTON et al 1983) developed during the commencement of the rifting and associated with the opening of the Gulf of Guinea, in the Late Jurassic to Early Cretaceous (BURKE et al, 1972; WHITEMAN, 1982). The crustal separation, typically preceded by crustal thinning, was accompanied by an extended period of thermally induced basin subsidence through the Middle – Upper Cretaceous to Tertiary times as the South American and the African plates entered a drift phase to accommodate the emerging Atlantic Ocean (MPANDA, 1997).



**Figure 1.** Location map of the study area showing sampling and VES points.

The basin is bounded in the west by the Ghana Ridge which is presumably an offset extension of the Romanche Fracture Zone while the Benin hinge line, a basement escarpment which separates the Okitipupa Structure from the Niger Delta basin and a continental extension of the Chain Fracture, bounds it in the east (Figure 2). The onshore part of the basin covers a broad arc-shaped profile of about 600 km<sup>2</sup> in extent and attains

a maximum width, along its N-S axis, some 130 km around the Nigerian – Republic of Benin border. The basin narrows to about 50 km on the eastern side where the basement assumes a convex upwards outline with concomitant thinning of sediments. Along the northeastern fringe of the basin where it rims the Okitipupa high is a band of tar (oil) sands and bitumen seepages (NWACHUKWU & EKWEZOR, 1989).



**Figure 2.** Generalized geological map of the Eastern Dahomey Basin showing area extent of the tar sand deposits (Modified after ENU, 1985).

**Table 1.** Regional Stratigraphic Setting of the Eastern Dahomey Basin (After Idowu et al., 1993)

AGE		FORMATION		LITHOLOGY	
		<i>Ako et al.</i> 1980	Omatsola and Adegoke 1981	Sandstone	
TERTIARY	EOCENE	Ilaro formation	Ilaro formation	Shale	
		Oshosun formation	Oshosun formation,		
	PALEOCENE	Ewekoro formation	Ewekoro formation	Limestone	
CRETACEOUS	MASSTRICHTIAN	ABEOKUTA FORMATION	ABEOKUTA GROUP	Araromi	Shale
	TURONIAN			Afowo	Sandstone and Shale
	BERREMIAN			Ise	Sandstone
PRECAMBRIAN		BASEMENT COMPLEX			

The lithostratigraphic units of the Cretaceous to Tertiary sedimentary sequence of eastern margin of Dahomey basin according to IDOWU et al (1993) is summarized in Table 1.

## **MATERIALS AND METHODS**

Geophysical, sedimentological and petrophysical investigation techniques were integrated in this study which required both field and laboratory measurements. Electrical resistivity data acquisition involved setting out Schlumberger and Wenner electrode configurations for Vertical Electrical Soundings (VES) and Electrical Resistivity Tomography (ERT), respectively. Zero/low frequency (no inductance) current was injected into the ground via two current electrodes, the injected current flow through the earth and generates potential difference across two potential electrodes. The generated potential difference was measured with the aid of ABEM 4000 SAS resistivity meter. High integrity data (r.m.s. < 5 %) which approximate the apparent resistivity of the subsurface layers were obtained by integrating the geometric factor of the electrode configuration used. Vertical Electrical Sounding enables 1-dimension measurement of variation in subsurface electrical properties with depth by systematically increasing the separation between the two current electrodes about a symmetrical center.

Two dimensional ERT measurements was performed using Wenner electrode configuration which allows determination of apparent resistivity values in the horizontal direction and variation in resistivity value with depth by increasing the electrode spacing. VES and ERT gave insight into the electrical property distribution of the earth's subsurface. Figure 1 presents the location map of the study area showing ERT profiles and VES locations.

### **Data Processing**

Data processing involved data quality check for spurious and erroneous data which may constitute noise. VES data were plotted on bi-log paper for partial curve matching using standard two layer curves and auxiliary Cagniard Graph (KOEFOED, 1979). This compares the observed data curves with theoretically generated standard curves and gave some electrical parameters such as thickness and resistivity values of each layer. The obtained layer parameters served as starting model for inversion of the field data using WinRESIST version 1.0 software. This helped to generate sets of earth models that represent the electrical properties distribution of the subsurface. Electrical resistivity subsurface model with high geological significance as well as least misfit between the measured and generated data was accepted. ERT data were also inverted using RES2DINV, version 3.4 developed by LOKE, 1999b.

The inversion software is based on the Least Squared Inversion algorithm which performs smoothness constrained by Least Squared Inversion based on finite element modeling.

### **Sedimentological and Petrophysical Analyses**

Tar sands samples recovered from borehole drilled to the deposit were analyzed in the laboratory for various granulometric and petrophysical analyses. Mechanical sieving was carried out using set of sieve size range from 75  $\mu\text{m}$  to 4760  $\mu\text{m}$ . The results of the various fractions were also employed to determine the sorting and skewness of the reservoir sands. The effective porosity of the tar sands was determined using a solid density test (displacement method). The core sample was immersed in water for ten minutes to allow for initial absorption in a measuring cylinder. The specimen was then transferred to a displacement vessel where it displaced a certain volume of liquid (bulk volume of specimen). The same sample after drying to a constant weight was pulverized in mortar and the resulting powder was carefully transferred into a half filled measuring cylinder with liquid. Rodding was then done at interval, to displace any air that may be trapped in it. Afterwards, the reading of the final level of the liquid in the cylinder was noted. The porosity of the tar sand specimen was determined using the mathematical relation below.

$$\text{Porosity}/\% = \frac{\text{Bulk volume} - \text{solid volume}}{\text{bulk volume}} \times 100$$

The permeability of the tar sand specimen was also carried out using the Falling Head Permeability Apparatus set. This method measures the hydraulic gradient and quantity of water flow into the sample, using a varying head of water during the test.

Permeability is obtained from the formula

$$K/(\text{cm/s}) = 2.3026 a L/A(\lg H_1 - \lg H_2)/(t_2 - t_1)$$

Where  $K$  is the coefficient of permeability is obtained from the formula

$a$  - cross-sectional area of the standpipe  
 $L$  - length of soil sample in permeameter

$A$  - cross-sectional area of the permeameter

$H_1$  &  $H_2$  - the heads between which the permeability is determined.

$t_1$  - time when water in the standpipe is at  $H_1$

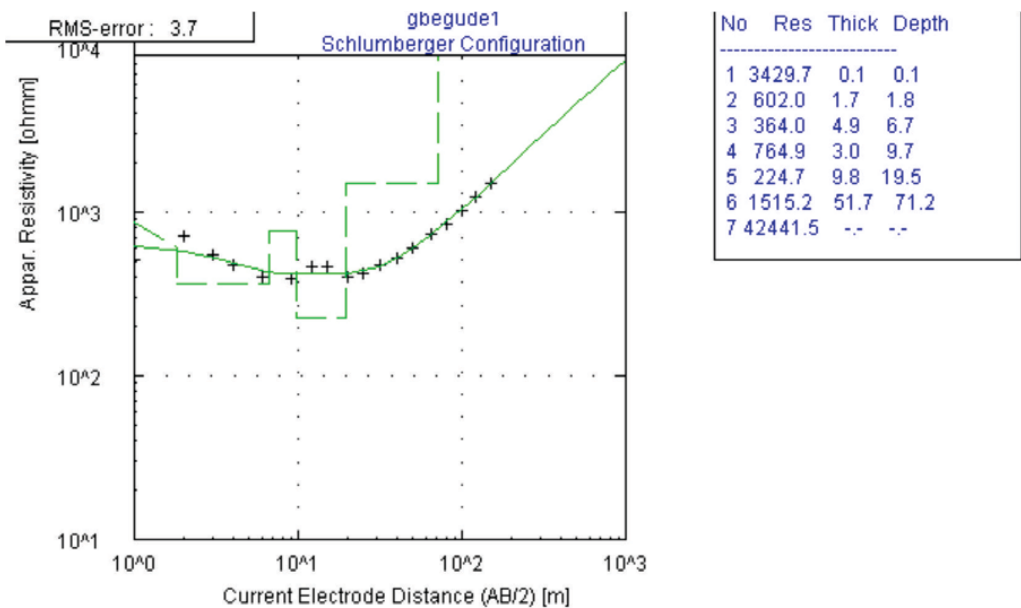
$t_2$  - time when water in the standpipe is at  $H_2$

The specific gravity and API gravity of the extracted oil was obtained by measuring displacement in water. The viscosity of tar extract was also done using a cone plate viscometer. The tar extraction was done using the Soxhlet extractor. This was achieved by placing the tar sands in the thim-

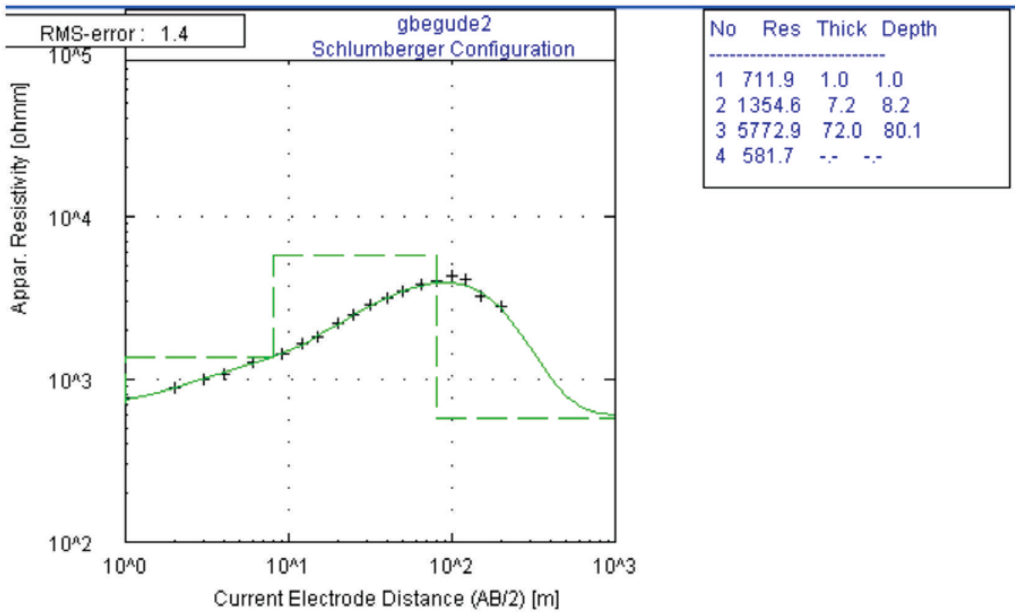
ble made from thick filter papers loaded in the main chamber of the apparatus and placed on a flask containing the extraction solvent. The solvent is heated to reflux, releasing its vapour to travel up the distillation arm. A condenser ensures that the solvent vapour cools and drips back into the chamber housing the tar materials. The chamber containing the solid material is slowly filled with the warm solvent. When the Soxhlet chamber is almost filled, it is automatically emptied by siphon side arm with the solvent running down into the distillation flask. This cycle is allowed to repeat many times, over hours or days.

**RESULTS AND DISCUSSION**

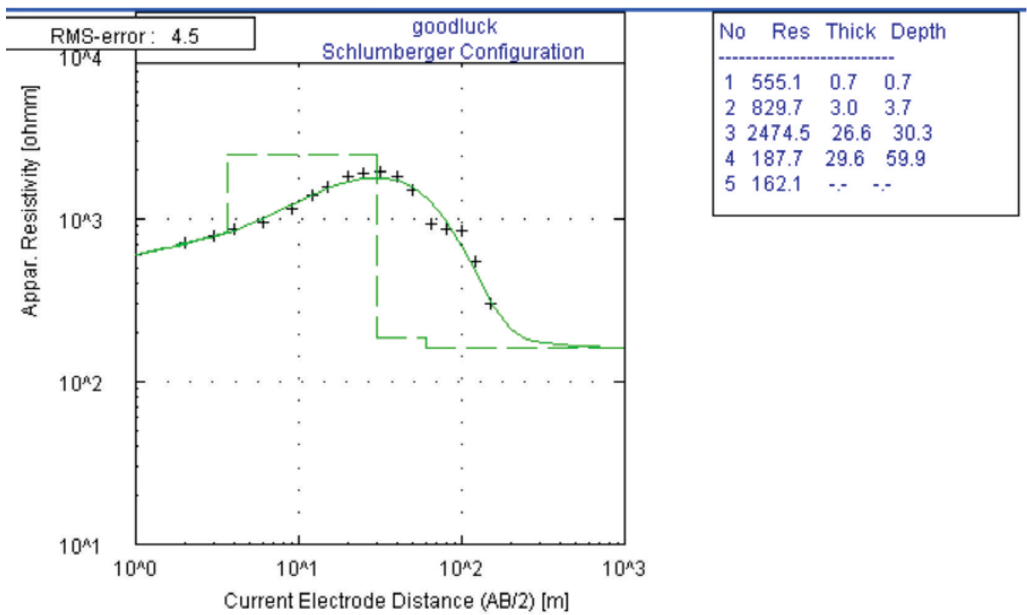
Electrical resistivity method has found wide and successful application both in surface and borehole measurements to differentiate hydrocarbon saturated region from saline water saturated sand on the account of very high resistivity signature of hydrocarbon pore fluids that are incapable of ionic conduction (WINSAUER et al, 1952). Representative resistivity VES curves obtained after 1-d inversion of the field data are presented in figure 3 (a–c). The interpretation of the resistivity layered parameters was constrained by core and drill cuttings information from a drilled borehole from where samples were



a)



b)

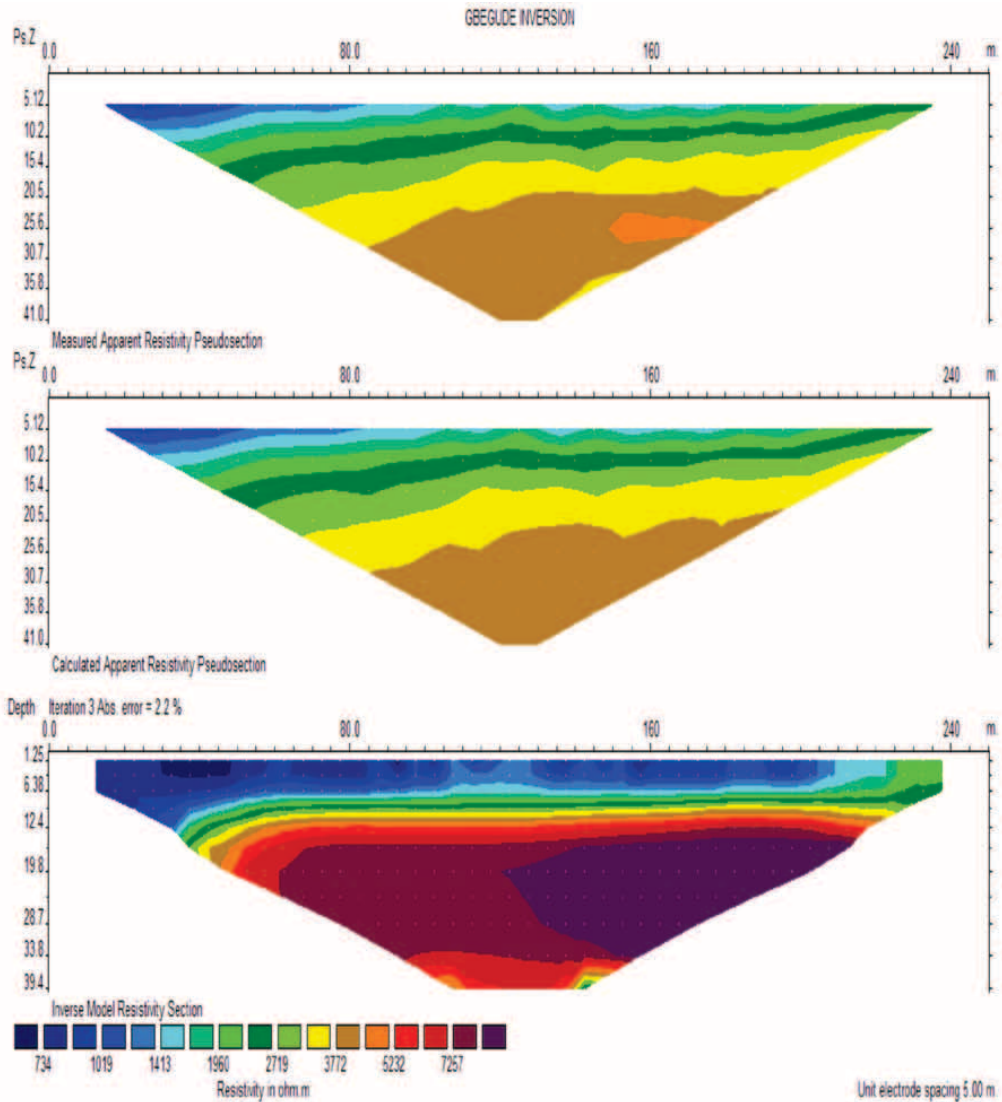


c)

**Figure 3.** VES Curves obtained from the Study Area

recovered for laboratory studies. The layer with the highest resistivity value corresponds to the section in the borehole with tar impregnated sand. The tar sands layers delineated from resistivity investigation range in thickness

from 17–72 m with resistivity values of 1515–5773 Ω m. The obtained results indicate a general reduction trend toward the west, in the tar sands layer thickness and resistivity. High resistivity values of the tar impregnated layer

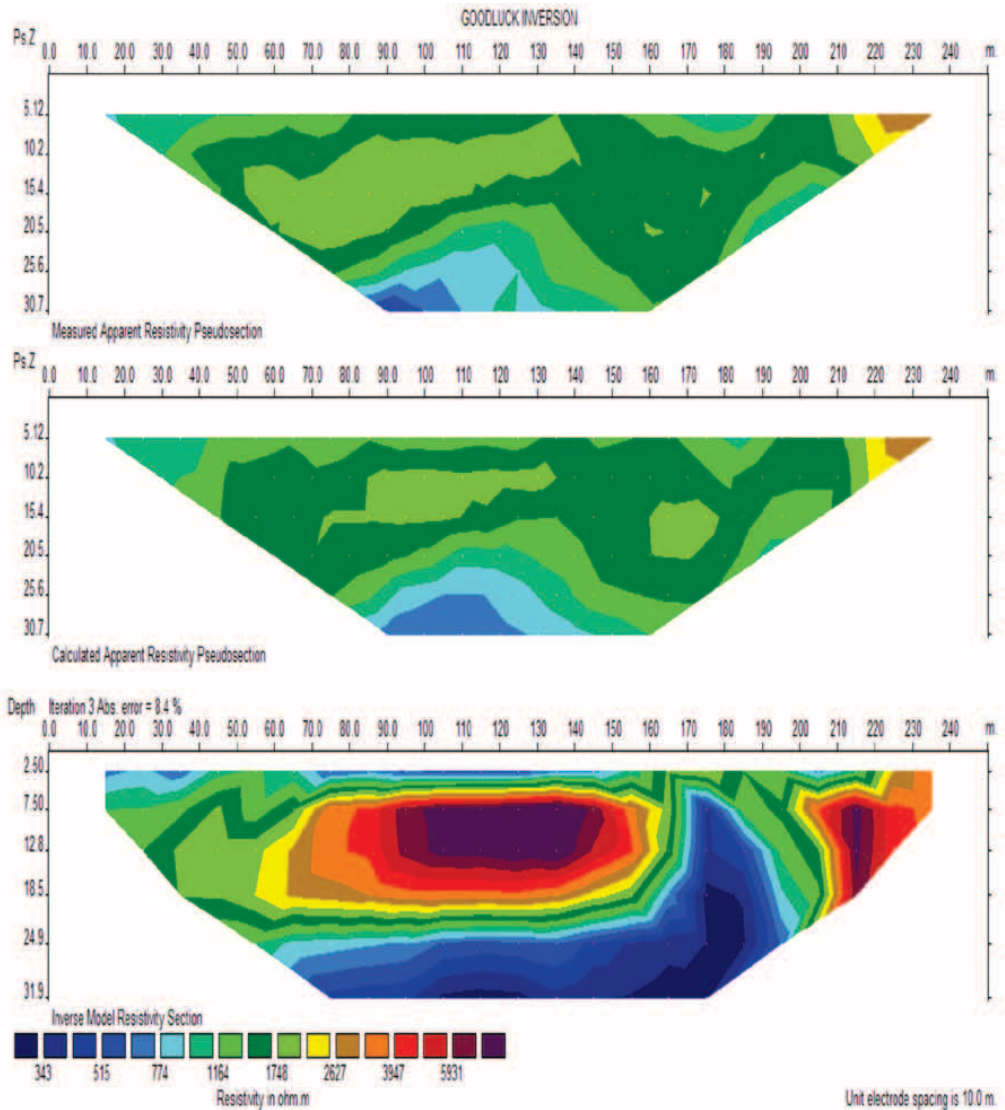


**Figure 4.** Raw data, pseudosection and 2-d resistivity inverted section across Gbегude II profile.



were recorded; this is likely due to the fact that the heavy hydrocarbon oils which fill the pore spaces are molecular compounds which are poor conductor of electricity. However, low resistivity tar sands deposits are also commonly

encountered in the southern part of the Nigerian tar sand belt. This is probably because the tar sands in this region are water wet (ADEGOKE et. al, 1981), where the incorporated/impregnated saline water enables ionic conduction.



**Figure 5.** Raw data, pseudosection and 2d resistivity inverted section across Goodluck profile.

Figures 4 and 5 present the ERT raw data, calculated pseudosection and 2-d inverted resistivity data across the field along the E-W profile. The plot also delineates the high resistivity layer to be tar impregnated. This agrees with VES results and borehole information.

### Sedimentological Analyses Results

The mechanical sieve analysis gave an average grain size distribution of the reservoir sand to range from  $\phi = 0.03$ – $0.55$  mm, which indicates a medium to coarse sands. The skewness of the reservoir sand was determined to ranges from  $-0.58$ – $0.47$ , indicating strongly coarse to strongly fine skewed according to (FOLK, 1974). This result defines a high energy of deposition at Ebute, Shofini and Bakue, but lower at Gbegude, thus accounting for the 2.5 % of fines in its composition. The sorting of the reservoir sands ranges in values from  $\phi = 0.82$  mm (moderately sorted) to  $\phi = 1.63$  mm (poorly sorted) according to Folks' 1974 classification, while the percentage of fines collected were composed of silt and kaolinitic clays in the range of 1–3 %. The summary of the granulometric analyses results is presented in table 2.

Depth of occurrence of the tar sand deposits affects the volume of voids as well as the precipitation of bitumen during migration by fines due to geopetal accumulation (LOMANDO, 1986

and 1992; DUTTON & FINLEY, 1988) which has the tendency to result in a reduction of pore throats and porosity. The moderate to high porosity values obtained for the reservoir sands, which range from 16–24 %, (COLE & CHRISTOPHER, 1992; WALLACE & JOHN, 1992, LOMANDO, 1992). The interconnectivity of pore spaces to transmit fluid is however obstructed by the precipitation of fines from migrating fluids which reduced the pore throats. In addition, the degree of sorting as well as the measure of skewness also affects the degree of reservoir's permeability. This is because a strongly coarse skewed reservoir sands is expected to have larger pore throats, which if interconnected is expected to be highly permeable. The permeability may be reduced however where the pore throats are blocked by fines in case of poorly sorted reservoir sands. Most of the reservoir sands are moderately sorted, which is a good reservoir quality. Permeability is also dependent on the effective grain size of the reservoir sand (SCHLUMBERGER, 1989). It can be stated from this study that the larger the effective grain size, the greater the permeability as evident in Table 3. More so, the presence or abundance of fines in a reservoir reduces the permeability of the reservoir. This was observed in the analyzed samples. It was observed that the poorly sorted reservoir sand at Gbegude with about 2.5 % of fines record the lowest permeability value of 143 mD. While the reservoir at Ebute

**Table 2.** Summary of the result of granulometric analyses of the tar sands deposit.

Sample	Mean $\phi$ /mm	Sorting $\phi$ /mm	Remark: Folk,1974	Skewness	Remark: Folk, 1974
Gbegude 3	0.033	1.5	Poorly sorted	0.34	strongly fine skewed
Shofini 12	0.55	0.82	Moderately sorted	-0.58	strongly coarse skewed
Shofini 13	0.26	1.63	Poorly sorted	0.47	strongly fine skewed
Ebute 14	0.53	0.93	Moderately sorted	-0.32	strongly coarse skewed
Bakue 18	0.52	0.94	Moderately sorted	-0.43	strongly coarse skewed

**Table 3.** Relationship between Reservoir Grain Size, Porosity and Permeability.

Sample	D10(mm)	Porosity (%)	Perm. k. (mD)
AB1	0.51	23.08	3053.8
B18	0.43	23.72	215.4
G1	0.87	20.78	887.53
G3	0.35	16.22	143.03
E14	0.45	23.36	236.44
SH12	0.47	21.9	257.9
SH13	0.42	23.32	210
M5	0.57	22.37	3826.74

**Table 4.** API gravity values of oil grades (USGS, 2000).

Light Oil 22.3 <sup>o</sup>
21.6 <sup>o</sup> Heavy Oil 10.0 <sup>o</sup>
6.5 <sup>o</sup> Extra Heavy Oil 0.1 <sup>o</sup>

and Shofini were moderately sorted with amount of fines less than 2 % and permeability values greater than 215 mD. Finally, from the study, the permeability values are found to be moderate to very high (COLE & CHRISTOPHER, 1992).

The API gravity values obtained in the area are all below 20<sup>o</sup>, this indicates that the tar sands are composed of Heavy and Extra Heavy Oils according to the USGS scale of oil grades (USGS, 2000), (Table 4). This implies that extracted bitumen is moderately biodegraded and contains good proportion of Asphaltene and Heavy Oil which are responsible for the high resistivity values of the tar sand obtained from the resistivity survey. The bitumen in this area is highly viscous with viscosity of 1080 cP and 1360 cP in Gbegude and Ago – Alaaye respectively. The bitumen content of the tar sand samples analyzed ranged from mass fractions 18 % to 30 %.

## CONCLUSION

The high porosity and permeability values obtained and the degree of sorting of the reservoir sands are indications of a good reservoir quality in the study area. Also, the viscosity and specific gravity values obtained from the analyses indicate highly viscous and low specific gravity oil. These, coupled with high asphaltene content are an indication of severe biodegradation. Moreover, result of API gravity equally showed that the deposits belong to the class of heavy oil. The biodegraded, low viscous low API gravity of the tar which impregnated the sands explains the high resistivity value of the tar sands deposit around the study area in addition to the fact that molecular compounds (hydrocarbons) are incapable of ionic conduction.

The reservoir characteristics of the tar sands in Gbegude area are similar to those earlier studied by other researchers, in that porosity values obtained fall between 16–24 %; percentage of fines ranges from 1–7 %, and are mainly composed of kaolinitic clay and silt; depth of burial ranges from 0 m to >50 m; tar sand reservoir is about 18–72 m thick.

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## Technological process and equipment selection for excavation of natural stone in Lipica quarry

### Izbira tehnološkega procesa in opreme za pridobivanje naravnega kamna v kamnolomu Lipica

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**Abstract:** Stone is an important part of nature. When man realised that stone is useful, they started to think of easiest methods of its exploitation. Through the centuries, there have been numerous research studies and development of expertise necessary for selection of natural stone, methods of its exploitation and most effective procedures for its processing. The development is still continuing today. Improvements in the field of technology have resulted in increased production, safer work procedures and transition from open surface to underground excavation methods. The article presents the development of quarry equipments, proper selection of the technological process and introduction of the new chain saw cutting machine in excavation of natural stone (i.e. limestone) in the quarries of the company Marmor, Sežana, d. d.

**Izvleček:** Kamen je pomemben del narave. Ko je človek spoznal, da je kamen uporaben, je začel razmišljati o njegovem najlažjem pridobivanju. Skozi stoletja so tekle mnoge raziskave in razvoj potrebnih znanj s ciljem izbire naravnega kamna, načina njegovega pridobivanja in postopkov najbolj učinkovite obdelave. Ta razvoj se nadaljuje tudi danes. Izboljšave na področju tehnologije niso omogočile le povečanja proizvodnje, temveč tudi varnejše delo in prehod s površinskega na podzemni način pridobivanja. V članku je predstavljen razvoj kamnolomske opreme, pravilna izbira tehnološkega procesa in uvedba

novega verižnega zasekovalnega stroja pri pridobivanju naravnega kamna – apnenca v kamnolomih družbe Marmor, Sežana, d. d.

**Key words:** underground excavation of natural stone, geological studies, mineral raw materials, chain saw machines

**Ključne besede:** podzemno pridobivanje naravnega kamna, geološke raziskave, mineralne surovine, verižne žage

## INTRODUCTION

Natural stone used for construction purposes are the rocks whose colour, compactness or other properties are appealing to a human eye. They were used by old civilisations to glorify their monarchs or even to make them equal to gods. It is precisely the use of stone that made it possible for many great achievements of the past to remain preserved until today.

A special and distinctive feature of natural stone is its hardness, stability and its possibility of shaping. Natural stone is unique and exceptional in itself, as its colours and structure are very different and dependent of the nature.

Beside physical and mechanical properties of stone, the excavation method is also influenced by mining and geological conditions as well as technical conditions of excavation. Judging from experience, the most problems in natural stone excavation are caused by tectonic influences, mainly cracking and fragmentation which, together with stratification and karstification, usually

significantly reduce the yield or even prevent further excavation of blocks of natural stone.

Additionally, the excavation processes and the final yield in a quarry are mostly influenced by the excavation method, the use of suitable equipment and utilisation of natural features of stone.

## DEVELOPMENT OF QUARRY EQUIPMENT

Natural stone is undoubtedly the material that has been used by man throughout the entire history. The prehistoric man exploited the stone by collecting it from the ground or breaking and digging to the depth or size easily lifted and transported. The stone was processed by means of stone and wooden tools. After discovery of metals, metal tools were used for stone processing. The man used stone for tools and weapons in the struggle against nature and for construction purposes. Beautiful stone blocks were used for making monuments, doorposts, portals, etc. The material was transported by oxen, horses, etc. <sup>[5]</sup>



Until a few decades ago, the exploitation of stone was based on making use of its natural properties, mainly the cracks which were used for breaking the stone into smaller pieces. All works were done on the surface, manually, with primitive tools such as mallets, chisels, picks and various simple levers. The pieces of stone appearing on the surface were carved by picks and mallets until they broke. The work was long-lasting and strenuous.

A true revolution in the quarry work was brought about by boring drills. The work was still manual. Natural features of sites were exploited. In winter, people poured water in cracks. Freezing water expanded the cracks and made breaking of stone easier. Hazelnut rods and oak wedges were also used; they were hammered into cracks and moistened with water. <sup>[2]</sup>

The development of pneumatic drilling tools additionally changed and increased the production. Using pneumatic drilling equipment, people drilled under and around the rock mass which was then split into smaller blocks by means of wedges and heavy mallets. In most cases, they made use of natural features of the sites (discontinuities, stratification, etc.), but they also used various emulsions, gunpowder and detonating cord to split the rock mass apart. <sup>[3]</sup>

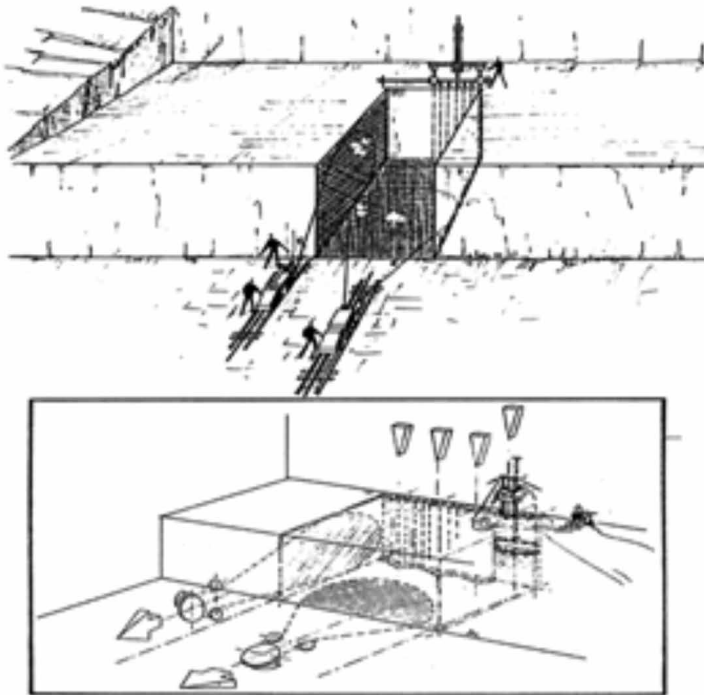
The development of quarry equipment continued with helicoid wire and quartz sand. This method was first used in the year 1854. In our country, it continued to be used by mid-1980s. At cutting sites, vertical bores with a diameter of 240 mm and 360 mm and horizontal bores with a diameter of 90 mm were first drilled. A 5.8 mm helicoid wire was threaded through the bores and used, together with quartz sand, for cutting of stone. An engine room with a diesel aggregate was required for the start-up. Water was used as an additive and a coolant. The cutting efficiency was low, amounting to 1.5 m<sup>2</sup>/h to 2.0 m<sup>2</sup>/h, depending on the hardness of the stone. The length of the wire system line was sometimes up to 2.5 km. <sup>[2]</sup> In the present time, helicoid wire has been replaced by diamond wire.

A new revolution in quarry mining was introduction of diamond wire saw. The first diamond wire saws came into operation in the 1970s. The cutting process is similar to the preceding technology; i.e. a combined method with previously drilled bores (34–90 mm in diameter) and diamond wire saw. The speed of cutting ranged from 8 m<sup>2</sup>/h to 12 m<sup>2</sup>/h, which meant new possibilities in exploitation and processing of natural stone. In the beginning, diamond wire saws with 30 kW (40 hp) motors were used, which allowed cutting of surfaces of up to 150 m<sup>2</sup>. <sup>[2]</sup> Today,

diamond wire saws with 19–56 kW (25–75 hp) motors are used, allowing cuts of up to 300 m<sup>2</sup>. The use of water and wet cutting is compulsory, as it extends the service life of the diamond wire. The use of diamonds depends on the structure, compactness and type of the stone.

Additional development of quarry equipment was brought about by the introduction of chain saw cutting machines. The machine's principle is similar to that of a power wood saw; however, the machine has larger di-

mensions and an additional hydraulic and electrical system. The most important component of the machine is a blade with a chain. The blades are of various lengths, ranging from 1.5 m to 7 m, depending on the use of the machine. Cutting of stone is performed by using a chain blade with “widia” or diamond plates mounted on it. Diamond plates are made of small grains of polycrystalline diamond introduced in the tungsten carbide base. The plates are mounted, in different directions, in brackets on the chain. We have an option of wet or dry cutting.



**Figure 1.** Illustration of exploitation by means of the drilling equipment and diamond wire saw <sup>[1]</sup>



**Figure 2.** A track chain saw and cutting elements <sup>[6]</sup>



**Figure 3.** An old and a new model of the chain saw machine for underground mining. Left: the Fantini G. 70 model on fixing pillars. Right: the new Fantini GU 70/R model. <sup>[6]</sup>

Chain saw cutting machines were first produced for open-surface exploitation shown in Figure 2. The construction of the machine allowed both horizontal and vertical cuts. In the beginning, machines for underground excavations were designed to have

the cutting machine mounted on fixing pillars which allowed raising and lowering of the cutting section (Figure 3 - left).

Deficiencies of older models encouraged the development of cutting ma-

chines towards greater mobility. So, presently, chain saw cutting machines are being used that consist of a single segment and have their own mobile unit. Due to their mobility, they can be used for both open-surface and underground exploitation.

The Fantini G.70 chain saw cutting machine has been used by the company Marmor, Sežana, d. d., since the year 2002. As evident from the photo, transportation of the machine requires a high-performance loader. Additionally, the connection to the control unit is done via hydraulic hoses which must be disconnected and reconnected for every movement of the machine. Machine setting procedures require a lot of time; approximately 2 h are needed for each cut. An advance section consists of four horizontal and three vertical cuts.

An upgrade to the old Fantini G. 70 cutting machine is represented by numerous new mobile models. At the company Marmor, Sežana, d. d., we have selected the Fantini GU 70/R model. The Fantini GU 70/R model has been upgraded with a mobile unit, problems with hydraulic hoses have been eliminated, its dimensions and mobility allow cutting of larger widths and lengths, rotation of the blade in several directions allows cutting of the rear wall. After finished cutting, the machine automatically corrects the cut in order to avoid the risk of cutting into the safety pillars. Diamond cutting elements are used for cutting. An advance section cut with the new machine consists of five horizontal and three vertical cuts.

Advance effects resulting from the introduction of the new machine com-

**Table 1.** Presentation of properties of both Fantini chain saw cutting machines<sup>[6]</sup>

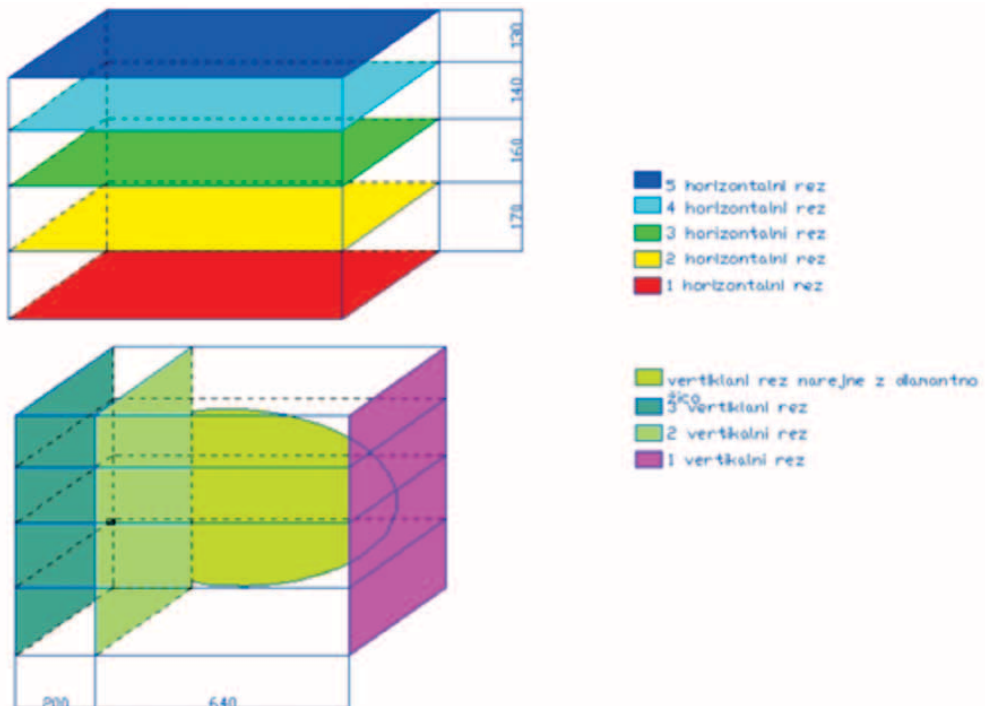
	Chain saw cutting machine Fantini G.70	Mobile chain saw cutting machine Fantini GU 70/R
Weight	6 000 kg	26 000 kg
Weight of the hydraulic unit	2 000 kg	-
Total installed power	52.2 kW	60 kW
Blade run speed	0–0.07 m/min	0–0.08 m/min
Hydraulic oil tank capacity	300 l	450 l
Cut width	38 mm	38 mm
Blade length	2 900 mm	3 200 mm
Minimum gallery advance	71 m <sup>3</sup>	85 m <sup>3</sup>
Minimum advance section cutting cycle	41 h	47 h
Maximum height of cutting	4.5 m	5.4 m

pared to the previous model:

- approximately 20 % more material excavated from a minimum advance section,
- the time required for setting the machine before operation has been cut in half,
- easier movement and faster retreat from the cutting location in case of danger,
- a new blade and electronics prevent the risk of cutting into the safety pillars,
- modified geometry of cutting the advance section (increased distances between cuts).

Beside the cutting equipment, natural stone excavation also requires high-performance loaders, powerful compressors, lifts, hydraulic rollers and water cushions with a water pump.

The effective cutting depth of the new Fantini GU 70/R machine is 3.2 m. The geometry of cuts consists of five horizontal and three vertical cuts. If compared to the previous Fantini G.70 machine, the distribution of horizontal cuts is changed by adding another horizontal cut which increases the height of the underground terrain from 4.5 m to 5.2 m or more. The distribution is adapted to



**Figure 4.** Geometry of distribution of cuts in the use of the new Fantini GU 70/R cutting machine

the best possible yield of material from an advance section. Lower distances between horizontal cuts have been increased in order to obtain blocks of maximum height dimensions for further processing. Certain horizontal cuts can be omitted, but due to the structure and cracking of the site, this might aggravate the work and increase the exploitation costs. As excavation at higher levels is more difficult, the distances between horizontal cuts are increasingly smaller with height. In the excavation of natural stone from quarries of Marmor, Sežana, d. d., the cutting geometry as illustrated in Figure 4 is used. Sometimes, a horizontal cut can be omitted, contributing to a better yield from an advance section.

### SELECTION OF EQUIPMENT

Quarry equipment requires careful selection, as the use of unsuitable equip-

ment significantly increases excavation costs.

Before selecting the machines, the following research should be done:

- geological studies must be made to establish the geological structure, reserves and quality of the mineral material,
- geomechanical studies must be made to establish the physical and mechanical parameters of the material, strength, abrasiveness, possibility of swelling, chemical and mineral structure.

Before selecting the equipment, an appropriate excavation method should be selected; i.e. either surface or underground excavation. On the surface, a method of excavation from top to bottom is used; the height of exploitation floors is usually 3 m to 6 m. In underground excavation, the combined



**Figure 5.** Open surface and underground excavation - Lipica 1 quarry.

chamber-and-pillar method is used. In it of great importance that at the first level the distribution of cuts is precisely determined, as it influences the final yield of material.

Selection of the excavation method or the proper cutting system depends on the type of the material, compactness, quantity and price of the material. In most cases, faster and better work requires combination of various cutting machines to obtain satisfactory excavation results.

Cutting equipment in quarries should be complemented by high performance loaders, as larger and more powerful machines make the excavation process easier and more economic. In excavation operations, the use of various bumper cylinders, water and air cushions is also required.

#### CUTTING PERFORMANCE COMPARISON

The reasons for underground excavation of natural stone are the following:

- geological properties of the site,
- selective excavation of natural stone,
- less environmental damage and less environmental noise,
- work is possible in any weather conditions,
- possibilities for the use of such underground locations after finished excavation works.

Because of the transfer to underground exploitation, a research is done on the impact of the underground exploitation method that is applied in Lipica II to the surface [8]. The results of the research have shown that the method of underground exploitation applied to Lipica II does not have an impact on the surface. As there is no movement in any direction, there is no deformation and the surface has stayed the same (as if no work is being done below). It has been expected that there will not be any impact to the surface, on the base [9], but because of the specificity of Lipica II, adapted research of [8] research had to be done.

Demand for natural stone blocks, increased production in the quarries, cost reduction in the process of excavation of natural stone and safer work operations are the main requirements regarding the excavation which have contributed to the development of a newer model of chain saw cutting machines.

Relocation of production from the surface to the underground required the development of technology suitable for underground excavation. Initially, chain saw cutting machines with fixating pillars were used (Figure 3 - left). The Fantini G. 70 machine consists of two segments: the cutting segment and the hydraulic control segment. The machine is transported to and from the cutting site by means of a loader.

Before the beginning of each cutting operation, it takes the operators approximately two hours to prepare the machines, set the blade in a horizontal position and to rotate the cutting elements. Before every movement of the machine, it is required to disconnect and arrange the hydraulic hoses. When making the first sections in a gallery, where fixation of pillars in the ceiling is not possible, stabilisation by means of chains is required. Problems may occur in the event of crumbling of the front section, with numerous instances of damage to the pillars.

Models of chain saw cutting machines are very different. Types of machines depend on the customers' requirements. There are several models of chain saw cutting machines. The machines are distinguished from each other by their intended use, cutting characteristics, dimensions and their electrical and hydraulic equipment. The newer machines have certain additional features:

- the machine's mobility,
- increased cutting height,
- the shape of the blade, an automatic blade levelling function has been added,
- faster movement in larger cutting widths,
- possible cutting of the back cut of an advance section,
- elimination of deficiencies of hydraulic cables,
- a computer to monitor the cutting

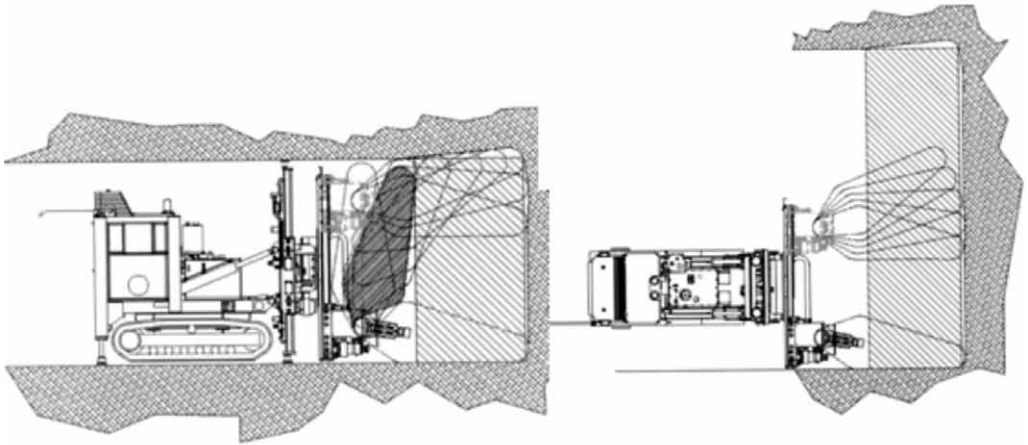
parameters,

- remote control of the machine.
- the weight of the machines allows easier start in making the first sections in a gallery.

With the new Fantini 70 GU/R machine, the deficiencies have been eliminated and improved. The comparison of the results between the machines G.70 and 70 GU/R is given in the table 1.

By introducing a new Fantini GU 70/R chain saw cutting machine, the company Marmor, Sežana, d. d., has acquired a machine of high quality and high performance. Compared to the old model, G.70, the minimum advance section (5.6 m × 4.5 m × 2.8 m) has been increased in height from 4.5 m to 5.2 m and in depth from 2.8 m to 3.0 m, thus harvesting by 20 % more material from a minimum advance section than by using the old model. Both the old and the new machine can be used to immediately start cutting the maximum width of a gallery. With the new chain saw cutting machine, approximately seven working days are required for an advance section of approximate size of 150 m<sup>3</sup>; with the older G.70 model, at least nine working days were required. The only problem that occurred was the construction of initial crossroads in a gallery, as the length of the new machine prevented its positioning in the direction of advancement. Therefore, we had to position the machine diago-

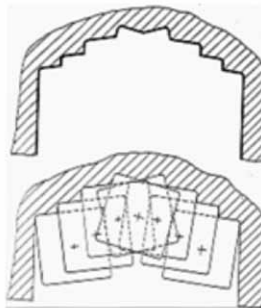




**Figure 6.** Illustration of making a vertical and horizontal cut by using the Fantini GU 70/R chain saw cutting machine and the XXL blade <sup>[6]</sup>



**Figure 7.** Comparison of initial cuts for a gallery with both Fantini machines <sup>[4]</sup>



**Figure 8.** Arrangement of cutting elements in a cut <sup>[4]</sup>

nally to the front and begin cutting in the material.

The arrangement of cutting plates on the chain (shown in Figure 8). The thickness of the cut is still 38 mm, and the system of the blade with cutting plates has remained the same. Different shaped on cutting elements are used: square, trapezoidal, star-shaped and round cross-cut sections of cutting elements. The shapes depend on the properties of the materials being cut as well as on the structure of “widia” plates. In our production, we use square-shaped “widia” plates, which can be rotated eight times, and round-shaped diamond cutting elements. The difference between the both is in price; the diamond plates are 10 times more expensive and more durable.

A proper distribution of horizontal and vertical cuts can also affect the yield of material, but it requires supervisor's constant monitoring and control, as the geological and safety conditions in a stone quarry change from one advance section to another.

## CONCLUSION

Technological development in the production of natural stone is still an ongoing process. In the exploitation industry, there is an increasing collaboration among the manufacturers

of working equipment and customers, as they together provide development of new and better equipment. New modifications to machines used in quarry work facilitate excavation and processing of the material. There are numerous manufacturers of chain saw cutting machines worldwide. Customers can choose from models that are most suitable for characteristics of their sites, their excavation preferences and prices. A great emphasis is on the production of suitable tools and cutting elements for different types of natural stone, as each material has its own properties. A new technology which is increasingly gaining in importance is the so-called waterjet technology, i.e. cutting of material by means of a water jet. The said technology is currently used primarily for processing of material in workshops.

Proper selection of technology requires previous elaboration of detailed geological and laboratory studies (mechanical and physical parameters of stone, chemical composition of the material), economic assessment of the site and consideration of nature protection conditions.

Based on results of the studies, we can select the optimal technology and technological processes of excavation to achieve satisfactory economic and technological results.

Despite continuous development of the technology, excavation of natural stone still requires consideration of natural features of sites and properties of stone, as they were observed in the past.

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## Železniška livarna v Šiški

### Railway-foundry in Šiška

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**Izvilleček:** Že kmalu po dograditvi Južne železnice med Dunajem in Trstom so v Ljubljani v Šiški postavili zelo dobro opremljene železniške vzdrževalne delavnice (t. i. Kurilnico) in v njihovem sklopu tudi livarno (leta 1868). Po zatonu parne vleke in drsnih ležajev se je potreba po ulitkih iz barvnih kovin zelo zmanjšala, z naraščajočim prometom pa močno povečala poraba zavornih oblog, ki so na železnici navadno izdelane iz sive litine s specifično kemično sestavo. Postavljena je bila nova livarna, ki se je z leti mehanizirala. Produkcija je rastla in v osemdesetih letih preteklega stoletja dosegla letno proizvodnjo okoli 3000 ton – pretežno za železniške potrebe. Po razpadu Jugoslavije se je povpraševanje po ulitkih najprej prepolovilo, kasneje pa, tudi zaradi uvedbe novih vlakov z diskastimi zavorami, še nadalje manjšalo. Livarna je prenehala delo oktobra 2003, delavci pa so bili prerazporejeni po drugih obratih.

**Abstract:** Soon after the Austrian Southern Railway was build between Vienna and Trieste, well-equipped railway maintenance workshops (so-called Engine-Shed) and a foundry (in year 1868) were set up in Šiška. After the fall in use of steam locomotives and sliding bearings, the need for castings made from non-ferrous metals declined significantly. However, the use of brake pads, for railway use usually made from grey cast iron with a specific chemical composition, was on the rise due to the increased traffic. A new foundry was built that eventually became mechanized. The production grew and in the 1980s, it reached approximately 3000 tons of iron per year, used mostly for railway purposes. After the breakup of Yugoslavia, the demand for castings reduced by two, and later, with the introduction of trains with

disc brakes, further decreased. The foundry shut down in 2003 and the workers were redirected to other industrial plants.

**Ključne besede:** železnica, livarna, siva litina, centrifugalni napajalniki, obloge za termitno varjenje tračnic

**Key words:** railway, foundry, gray cast iron, centrifugal feeders, refractory molds for thermit process casting of rails

## Uvod

Pestra geološka struktura ljubljanske kotline in pomembne trgovske poti skozi njo so imele med drugim za posledico, da so se njeni prebivalci že vsaj 2000 let pred našim štetjem ukvarjali tudi z ulivanjem kovinskih predmetov (kalupi in ulitki najdeni pod kolišči in ob njih na Ljubljanskem barju). Znano je, da je bila na Rebri pod Ljubljanskim gradom v poznem srednjem veku livarna zvonov in topov, Valvazor pa je svoj znameniti kip Marije, ki še danes stoji na stebru pred Šentjakobsko cerkvijo v Ljubljani, ulil pred dobrimi tristo leti po svojem postopku v livarni mojstra Schlaga pred ljubljanskimi Karlovškimi vrati, kar je tudi bogato dokumentiral (Philosophical Transactions, London in Acta eruditorum, Leipzig). Tradicija livarstva pri nas očitno nikoli ni povsem zamrla, celo več: Slovenija je dandanašnji po proizvodnji ulitkov na prebivalca med prvimi deželami na svetu, v Ljubljani pa sedaj deluje ena največjih livarn magnezija v svetovnem merilu! Drobec v mozaiku – zdaj je to že zgodovina – slovenske-

ga livarstva je tudi Železniška livarna v Šiški (slika 1), kot se imenuje ta predel Ljubljane.

## KRATKA ZGODOVINA

Že kmalu po dograditvi Južne železnice se je pokazala potreba, da se vzdrževalnim obratom, ki so jih postavili sredi polja nasproti železniške postaje v Šiški, priključi tudi livarna. Po nekaterih podatkih se je to zgodilo leta 1868, ulivali pa so rdečo kovino (ventile, ohišja ...) in skoraj gotovo prelivali drsne ležaje (po ohranjeni in še vedno delujoči peči sodeč). Po prvi vojni oziroma razpadu Avstro-Ogrske monarhije so livarno rdeče kovine preselili v Maribor (ustno K. Rustja). Ker pa se je pokazala potreba po sivi livarni (zavorni vložki ali zavornjaki, razna ohišja, rešetke kurišč za parne lokomotive itd.), so v Šiški postavili kupolko v današnji Kalilnici oziroma Kovačiji in delo začeli leta 1920 (dimnik še stoji) (slika 2). Proizvodnja je rasla in je bilo treba misliti na novo stavbo, kar se je zgodilo sredi druge vojne, in če

bi ta trajala še kak mesec dlje, bi Livarna verjetno imela tudi fasado, praviho. Sprva je bila v stavbi garaža za železniški avtopark in šele leta 1948 je v njej stekla proizvodnja. Naslednji mejnik je leto 1978, ko je bila proizvodnja deloma avtomatizirana. Gostol je dobavil konvejer in avtomatiziral pripravo peska. Ob koncu osemdesetih let preteklega stoletja je proizvodnja dosegla dobrih 3000 t letno (max. 3206 t), z osamosvojitvijo pa sprva padla na okoli 1500 t, kasneje pa na dobrih 1000 t raznih ulitkov. Dne 10. oktobra 2003 je prišlo do težje obratne nesreče, kar je bil dokončni povod za zaprtje Livarne teden dni kasneje (sicer so Livarno skušali zapreti že od leta 1960 naprej),

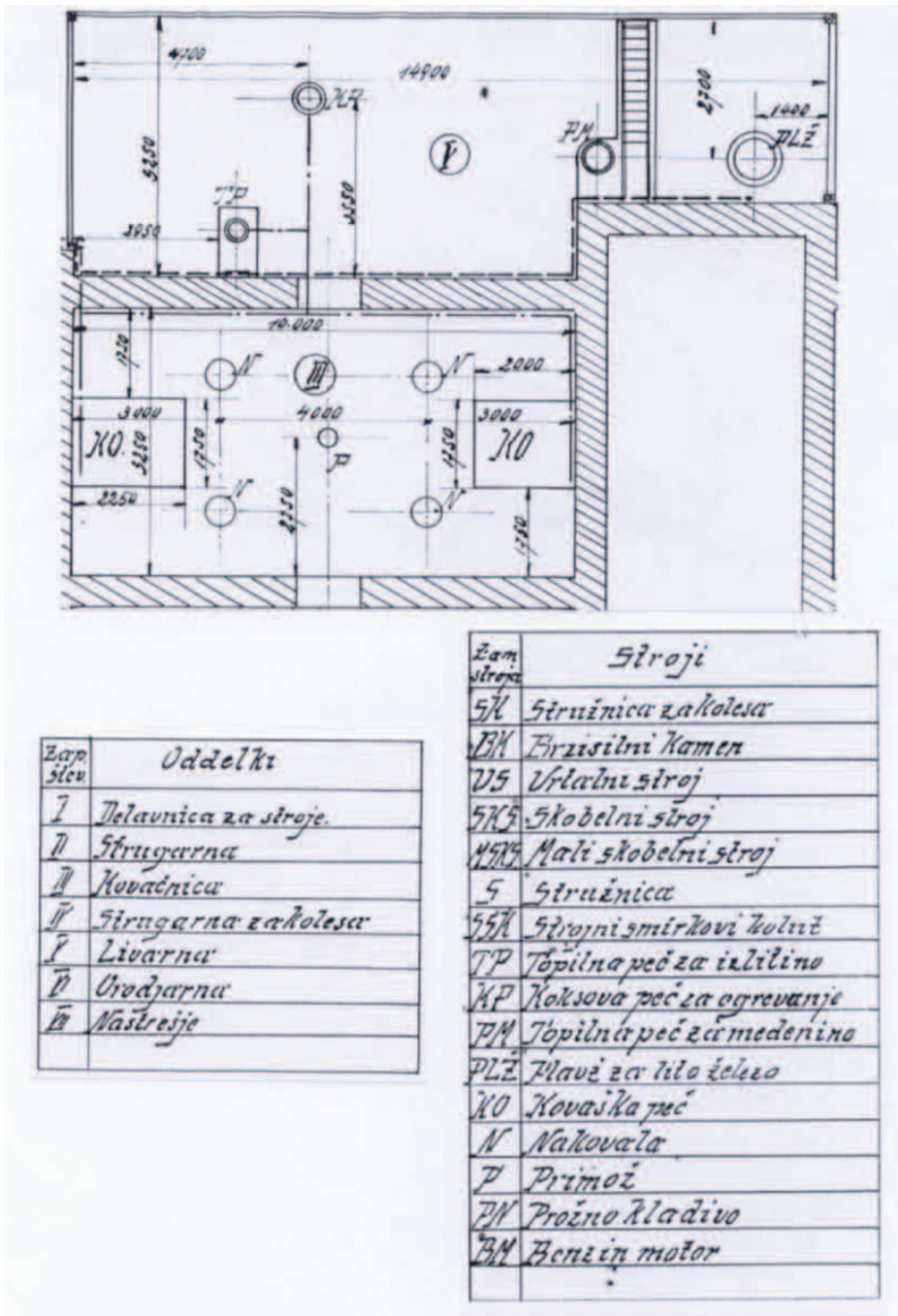
delavci pa so bili prerazporejeni po drugih obratih. Po dostopnih podatkih je Železniška livarna med svojim delovanjem proizvedla okoli sto tisoč ton ulitkov iz sive litine (v najboljših časih več kot 200 000 kosov raznih ulitkov na leto).

### STROJI IN OPREMA

Do modernizacije je delo v livarni potekalo pretežno ročno, tako kot še danes v večini majhnih livarn (slika 3). Prvi formarski stroji so bili ročni. Z leti se je oprema dopolnjevala, nabavljeni so bili prvi pnevmatski formarski stroji (foromat 10 , kasneje še 20, pnev-



**Slika 1.** Železniška livarna v Šiški – pogled s severovzhoda



Slika 2. Izrez iz Situacijskega načrta Kr. drž. žel. Prve delavnice za stroje v Ljubljani (okoli leta 1920)



matski livarski nabijači itd.). Notranji transport je potekal na vozičkih po ozkotirnih progah ob livarni in skozi njo na ročni pogon. Na razpolago je bilo le eno mostno dvigalo, izgotovljene forme pa so se zlagale v t. i. »štose« in »cvingale«.

Do temeljitega preobrata je prišlo z rekonstrukcijo (na osnovi elaborata in pod vodstvom inž. Sergeja Jegliča) (slika 4). Škoda je le, da tedaj niso nabavili linije Disamatic, ki je bila v tistem času baje le nekaj dražja od vgra-

jenega postrojenja, ki ga je projektiral in dobavil GOSTOL (Goriške strojne tovarne in livarna). Kakor koli že, srce livarne je bila t. i. linija, sestavljena iz šestih formatov 10 (in nekaj več v rezervi oziroma na popravilu), avtomatske priprave peska, konvejerja in dveh kupolk, ki sta talili izmenoma. Manjše serije raznih ulitkov se je, če je bilo mogoče, formalo na liniji, sicer pa v t. i. ročni formariji, kot smo jo imenovali. Tu smo imeli dva formata 20 ali pa smo forme klasično ročno izdelali. Ulivalo se je na posebni valjčni progi.



**Slika 3.** Železniška livarna pred rekonstrukcijo (1978)

Livne lonce smo na notranji strani izdelali z nabijalno maso (Kremen, Novo mesto), pred ulivanjem pa smo jih sušili in ogrevali s plinskim gorilnikom z odprtim plamenom (2 kg plina na uro). Tudi modelne plošče na foromatih smo grelji s podobnimi, le precej manjšimi plinskimi grelniki.

Čistilnica je imela Gostolov čistilni oziroma peskalni stroj s kovinsko verigo, peskalo pa se je z jeklenim granulatom povprečne zrnatosti 1 mm (Muta), ter več brusilnih strojev. Uporabljali smo bakelitne brusne plošče za sivo litino (Comet, Zreče). Težava je bila le v tem, da je včasih katero razneslo.

Notranji transport kot tudi polnjenje čistilnega stroja se je navadno opravilo s posebej prirejenim 2,5-tonskim viličarjem.

Pod livarno je spadala tudi izdelava kalupov za termitno varjenje tirnic. Za te kalupe (do 15 000 kompletov na leto), pa tudi za izdelavo raznih jeder po CO<sub>2</sub>-postopku, smo uporabljali dva pnevmatska strelna stroja (vzhodnonemški izdelek, tako kot foromati). Livarna je imela centralno odse-sovalno napravo. Ta je bila v bistvu precej velik vodni sesalnik (60 kW), ki pa nam je delal velike težave zlasti pozimi in nikoli ni kaj prida deloval zaradi premajhne kapacitete. Kasneje

je bil zamenjan z vrečastim filtrom, ki za temperaturne razlike sicer ni bil bistveno občutljiv, pač pa za dež. Montirali so nam ga namreč pod kap, elektronika za krmiljenje izpihovanja vreč pa v takih razmerah rada odpove oziroma pride do prebojev. Podoben filter, le precej manjši (15 kW) in starejši, je bil nameščen ob čistilnici in je odsesaval prah iz čistilnega in brusilnih strojev. Ta je imel pnevmatsko krmiljenje izpihovanja, ki pa je pozimi prerado zmrznilo.

Originalna stresalna rešetka je bila izjemno glasna. Delavec, ki je delal ob njej, pa je bil na velikem prepihu, zato smo jo morali zamenjati z novo, boljše konstrukcije, in jo delno prilagoditi našim potrebam.

Staro litino smo pripravljali za pretaljevanje v razbijalnici (okoli deset metrov visok stolp z vitlom in okoli tona težko kroglo) na posebni hidravlični preši ali pa ročno s težkimi kladivi.

Pomemben del livarne je bila nekoč modelna mizarina, ki je bila relativno dobro opremljena in je imela zaposlenih več mizarjev. Z leti so se potrebe po novih modelih tako zmanjšale, da so bila potrebna le še občasna manjša popravila (kitanje, barvanje) obstoječih. Kovinske modele pa so tako že od nekdanj izdelovali in vzdrževali orodjarji, strugarji in rezkalci.



**Slika 4.** Delo v livarni je bilo po rekonstrukciji v marsičem močno olajšano.

Izdelava armatur za zavornjake je prvotno spadala k delavnici za izdelavo rezervnih delov za železniška vozila, šele zadnja leta pa pod livarno. Armature smo izdelovali na ekscentričnih prešah, krivinski radij pa popravljali ročno na šabloni in s kladivom, saj so imeli materiali praviloma različno vzmetnost. Armature so morale biti pred vlaganjem v forme povsem čiste (brez škaje, maščob ali rje), sicer so se pojavile razne težave. Čistili smo jih v posebnem bobnu, kjer so se trle med seboj, bolj zapletene pa v čistilnem

stroju. Prav zadnje leto obratovanja livarne smo napravili novo petstezno orodje za rezanje in luknjanje armatur.

Za pogon pnevmatskih strojev smo imeli v Šiški centralno kompresorsko postajo s tremi kompresorji, in sicer:

- več kot sto let star batni Ingersol-Randt (45 kW),
- pol mlajši Spiros (90 kW),
- še malo mlajši Fagram (90 kW).

Navadno sta zadnja leta komprimirala zrak slednja dva – ali eden ali drugi,

Ingersol pa je bil zlata rezerva. Zraka je bilo ob polni zasedenosti kapacitet v livarni ravno še dovolj. Po ukinitvi proizvodnje v livarni pa so, kot kaže, tudi kompresorji imeli vsega dovolj in so drug za drugim »zaribali« ali pa jih je celo razneslo. Na srečo brez hujših posledic.

Inštalirana električna moč v livarni (vključno s kompresorsko postajo) je bila okoli 0,5 MW, seveda pa vsi stroji navadno niso bili vklopljeni istočasno. Kljub temu pa je poraba elektrike na območju železniških delavnic v Šiški vztrajno rasla, kar je bila konec osemdesetih že resna težava, poleg občasnih izpadov električne napetosti, seveda. Za pogon ključnih naprav v livarni se je v takih primerih (podpih kupolk, dvigala, razsvetljava, priprava peska) uporabljal električni agregat Torpedo z avtomatskim vklopom (150 kW), ki je bil (oziroma je še) nameščen ob kompresorjih. Za rezanje konic v porabi električne energije na območju vseh delavnic v Šiški pa je bil nabavljen računalniški sistem, ki je v takem primeru najprej izključil kalilne peči (80 kW in 45 kW), potem pa zaporedoma stručnice za kolesne dvojice (vsaka po 80 kW). No, potem pa smo se osvobodili oziroma osamosvojili. Proizvodnja je padala, tozadevne težave pa so postale preteklost ...

## DELOVNI ČAS

V letih najintenzivnejše proizvodnje so prvi delavci začeli delo okoli druge ure zjutraj (kurjenje kupolk, zalaganje peči in priprava taline), ob šestih pa se je navadno že ulivalo. Glavnina je delala do dveh, bolj zagnani pa tudi še popoldne (navadno so ulivali t. i. »strojno litino«, razkopavali forme, izdelovali kalupe itd.).

V tistih letih nas je bilo v livarni zaposlenih do 60 delavcev (vzdrževalna skupina je bila posebej, določena dela so delali drugi obrati – armature na primer), fluktuacija pa velika. Z osamosvojitvijo so se razmere korenito spremenila. Potrebe po naših proizvodih so se v nekaj letih prepolovile. Prilagajali smo se na vse mogoče načine. V začetku devetdesetih let smo najprej spremenili delovni čas tako, da smo vsi začeli delati ob šestih, litina pa je bila na žlebu ob deseti uri, sčasoma pa smo morali tudi ta urnik prilagoditi še zmanjšanim naročilom. Leta 2003 je bilo v livarni zaposlenih še 24 delavcev (skupaj z vzdrževalcema), ulivali pa smo vsak drugi delovni dan, dan brez ulivanja pa smo porabili za vsa druga dela, ki jih je bilo treba opraviti – npr. pripraviti litino, jedra, forme, armature, očistiti in obrusiti ulitke, popraviti stroje itd. Da nam je uspelo z relativno majhnim številom delavcev vse to postoriti, je bilo mogoče zato, ker nam je z leti uspelo delno mehanizirati notra-

nji transport (posebno prirejen viličar za polnjenje čistilnega stroja), urediti transportne poti (betoniranje, asfaltiranje) in notranji transport zmanjšati na najmanjšo mogočo mero ali ga celo eliminirati (pnevmatsko polnjenje silosov z novim peskom), z uporabo novih materialov (termobeton pri obzidavi kupolk, keramični filtri idr.), z optimiranjem ulivnih sistemov in na splošno z zmanjšanjem izmeta ter seveda s stalno skrbjo za mehanizacijo, vključno s skrbjo, da so bili vitalni rezervni deli vedno na zalogi. In ne nazadnje – v livarni smo uvedli skupinski dopust, ker drugače enostavno ni šlo oziroma ne bi imelo smisla. Za kolikor toliko sinhrono delovanje livarne je bila namreč potrebna neka minimalna zasedba. Zadnja leta smo zadostno število delavoljnih delavcev zagotavljali prek Biroja za delo.

Beneficirana delovna doba se je z leti krajšala in je bila ob zaprtju livarne dva meseca na dvanajst mesecev za redno zaposlene delavce v proizvodnji.

Pečarji, ki so vzdrževali kupolke, so bili zaradi izjemnih delovnih razmer prosti, ko je bilo delo opravljeno. Talilci so v osemdesetih letih delali vsak drugi delovni dan (imeli so precej podaljšan delavnik zaradi popoldanskega ulivanja, potem pa so morali še pospraviti pod pečmi), zadnja leta pa so imeli le še dodatek v urah glede na ure, prebite ob kupolkah. Podoben dodatek

so imeli tudi tisti delavci, ki so ulivali, vendar le na ure, prebite pri ulivanju. Prvotno so se nadure izplačevale (v livarni jih je bilo tudi več kot 10 000 na leto), zadnja leta pa so se praviloma lahko le izkoristile.

## KADRI

V vseh teh letih so šle skozi livarno stotine delavcev, večinoma brez izobrazbo ali z njo, livarjev pa je bilo relativno malo. Vzrok je bil verjetno tudi v tem, da so metalurgi prišli v vodstvo Livarne šele konec sedemdesetih let, in pa splošna miselnost, ki je livarje, njihovo znanje, delo in znoj podcenjevala. Relativno slabe plače so seveda na kvaliteto dela posredno slabo vplivale. Po osamosvojitvi se je položaj korenito spremenil. Mnogo delavcev je odšlo in kljub zmanjšani proizvodnji smo morali zaposliti nove, vsak delavec pa je moral obvladati po več delovnih mest. In tako se je zgodilo, da je Livarna imela pri dobrih tridesetih zaposlenih kar pet metalurških tehnikov. Od teh so trije delali v proizvodnji, kjer so imeli še vedno višjo plačo kot v prejšnji službi. Žal jim nismo mogli ponuditi njihovi izobrazbi primernih delovnih mest, niti plače. Z leti je vseh pet postopoma odšlo. Eden je odšel na svoje in ima doma sivo livarno (Jani Kopač), drugi pa v razne službe, ki s stroko niso imele nič skupnega.

Med delavci, ki so bili zaposleni v naši livarni, ni ravno veliko znanih ljudi, pa vendar. Eden med njimi je narodni heroj Tine Rožanc. Po poklicu je bil čevljar. Dobrih dvajset let je delal v naši livarni, in to je bila tudi njegova prva, edina in zadnja služba. Kot občinski odbornik v Pirničah, kjer je bil doma, je bil tudi skrbnik osirotelega Staneta Rozmana, kasnejšega legendarnega komandanta.

Drugi, Metod Trobec, ima povsem drugačen sloves. Njegov tedanji nadrejeni je vedel povedati, da je bil to edini delavec, ki se ga ni dalo spraviti v red. Na srečo v livarni ni bil dolgo ...

## KLIMA

Naša livarna je imela to srečo, da je bila zgrajena še po starih, preizkušenihih vzorih. Prvotno je bila dolga okoli 40 m, široka 15 m in visoka dobrih 20 metrov. Kasneje je bila podaljšana proti severu in dodanih je bilo več večjih ali manjših prizidkov ter napuščev, tako rekoč okoli in okoli livarne. Zlata vreden je bil nadstrešek z loputami skoraj čez celo sleme na strehi livarne. Lopute smo poleti odprli, čez zimo pa so bile zaprte. Z leti smo odsesavanje in s tem ventilacijo v obratu z raznimi vrati, zasloni in podobnim precej dobro uredili, tako da se je le redko zgodilo, da se zaradi dima ali prahu v zraku ni videlo skozi livarno. Dimne pline

okoli kupolk, ki so se sproščali zlasti pri odtakanju žlindre in so bili precej nadležni ter nikakor ne zdravilni, smo odsesavali kar z ventilatorjem za podpih peči, ki je bil nameščen v prvem nadstropju ob kupolkah.

Izjemno vroča poletja zadnjih let so nas spodbudila k razmišljanju o hlajenju strehe, o adiabatnem hlajenju livarne (podobno kot je v uporabi na kurjih farmah) in še čem (na »air condition« tako ni imelo smisla niti pomisliti). Do realizacije hlajenja ni prišlo, pa smo zato tedaj, ko je zunanja temperatura preseгла 27 °C tri dni zapored in se je livarna dodobra razgrela, začeli delo ob četrti uri zjutraj in delali do dvanajste ure, da smo nekako preživeli. Kasneje, ko prometne zveze tega niso več omogočale, pa smo delali od šestih do dvanajstih. Podoben je bil prehod nazaj na običajen delovni čas.

Huje pa je bilo pozimi. Snovalci odprševanja so namreč pozabili na temeljno pravilo ventilacije, pa tudi klimatizacije, namreč, če hočeš iz nekega prostora zrak odsesavati, ga moraš vanj tudi dovajati. Tega slednjega pa ni bilo. In tako so nam marsikatera na tračnicah nad podbojem obešena drsna vrata pozimi stala postrani, skozi vsako špranjo v zidu pa je vleklo. Prvotno prav v osrednjem prostoru livarne ni bilo prave kurjave in zlasti po vikendih, še bolj pa po daljših praznikih, ko so se litine na konvejerju in peči ohladile, smo imeli

z zagonom proizvodnje neizmerne težave. Imeli smo sicer dva termogena (po 6 kg goriva na uro), ki pa v hudem mrazu nista zadoščala, razen tega sta iz znanih razlogov bolj ogrevala streho kot pa samo livarno. Hidravlično olje se je zgostilo, forme so primrznile na palete, uteži na forme, voda v ceveh pa je zmrznila, včasih je katero tudi razneslo. Zrak oziroma klima v livarni pa je bila odlična, le precej mrzlo je bilo.

## EKOLOGIJA

Največja težava večine livarn so dimni plini ter prah različnega izvora, in mi nismo bili nobena izjema. Prah iz proizvodnje (stresalna rešetka, priprava peska, čistilni stroj itn.) nam je z leti uspelo dobro očistiti z vrečastimi filtri. Težje je bilo ta problem rešiti pri kupolkah. Sprva so se kape na njih samo hladile, voda iz vodovoda pa je različno velike prašne delce spirala v peskolovne jame, od tod pa je tekla v kanalizacijo. Včasih se je tudi kaj prelilo.

Povečane zahteve glede dovoljene emisije prahu (vse drugo je bilo v dovoljenih mejah) so zahtevale spremembo konstrukcije kap na kupolkah. Namestili smo novo visokotlačno črpalko, na kapah smo namestili vence s posebnimi šobami, odpadno vodo pa napeljali v 60 kubičnih metrov veliko odsluženo železniško cisterno, ki smo jo postavili ob livarni. V njej se je voda

umirila, pepel se je usedel na dno cisterne, očiščena voda pa je šla nazaj v črpalko. Prvotno je k vsej napravi spadal še ciklon in polž za iznašanje usedlin iz njega. Zaradi prevelikih težav v zimskem času in zmanjšanja proizvodnje smo ciklon kasneje opustili in je voda tekla kar direktno v cisterno. To smo morali očistiti nekajkrat na leto. In so prišle nove zahteve: še manj prahu v dimnih plinih. V tem primeru bi bil verjetno edini izhod ohlajanje dimnih plinov in filtriranje preko vreč, vendar se nam s tem problemom že ni bilo treba več ukvarjati, ker so nam livarno prej zaprli.

Razen jeder, izdelanih s CO<sub>2</sub>-postopkom, drugih problematičnih materialov zavestno nismo uporabljali, niti jih skušali uvesti v proizvodnjo. Količine odpadnih peskov in prahu iz filtrov pa so bile znatne in so tako rekoč dnevno potovale na deponijo Barje (prvotno povprečno po en zabojnik na dan, kasneje ustrezno manj).

## VARSTVO PRI DELU

Zadnja leta nas je bilo že tako malo, da je večina delavcev v enem delovnem dnevu delala najmanj na dveh delovnih mestih. Zjutraj se je na primer delalo v »štancariji«, potem pa se je pripravljalo vložek in zalagalo peč, kar pomeni diametralne klimatske razmere, kar je bilo nevšečno zlasti pozimi. Zato je

imel vsak delavec najmanj dve delovni obleki, od tega vsaj eno podloženo za zimske razmere, več parov delovnih čevljev, pa tudi škornjev, saj se je marsikaj dogajalo, kot že omenjeno, ne samo v livarni, pač pa tudi okoli nje na prostem, med lužami, snegom in še čim. Zagovarjali smo stališče, da je primerna delovna obleka in obutev mnogo cenejša kot kakršna koli bolniška. Res, zgodilo se je celo, da v livarni cel mesec ni bil nihče bolan!

Nabava takih zaščitnih sredstev je bil težji problem. Vedno se je našel kdo, ki je rad »šparal«, pa naj stane kolikor hoče. Do zadnjega je bilo treba kar naprej prepričevati odgovorne za nabavo, da delovni čevlji s plastičnim podplatom ne spadajo v livarno, da morajo biti šivani, usnje kvalitetno, podplat pa gumijast z izrazitim profilom, potem še, da delovne bluže, hlače in pajaci ter celo vezalke na čevljih ne smejo biti izdelani iz plastičnih materialov, da ni vseeno, kakšna so zaščitna očala (poškodbe oči so bile v čistilnici oz. pri delu na brusnih strojih relativno pogoste), da večnih težav z zaščitnimi rokavicami niti ne omenjamo (porabili smo jih res veliko).

Opeklinam se v livarnah zaradi narave dela ne da izogniti. Na srečo se opekline, ki so posledica brizgov sive litine, nasprotno od aluminija, zdravijo relativno hitro. Večinoma ni bilo hudega, težjih poškodb je bilo le nekaj. Najtež-

ja nesreča je bila brez dvoma tista, ki se je zgodila 10. oktobra 2003 in je posledično tudi povzročila zaprtje livarne. (Mimogrede – vsa čast in slava reševalcem z Reševalne postaje Ljubljana. Prvi, z motorjem, je bil v Livarni že nekaj minut po nesreči, drugi, z avtomobilom, pa le nekaj kasneje). Zanesljivo pa do nesreče ne bi prišlo, če bi livno dvigalo tedaj že imelo radijske komande, za kar pa smo si zaman prizadevali.

## ORGANIZACIJA PROIZVODNJE

V časih največje proizvodnje v osemdesetih letih so bili v vodstvu Livarne poleg obratovodje (v tistem času so bili to metalurgi Vilijem Pobežin, Ratko Matić, Jože Golob, Ratimir Branica in zadnjih slabih dvajset let Aleš Lajovic) zaposleni še:

- poslovodja talilnice in čistilnice (Anton Bizjan),
- poslovodja ročnega in strojnega formanja (Franc Tomažič),
- normirec (Janez Dolničar) in
- administratorica (Ivanka Križelj).

Skupinovodje so delali v proizvodnji, skupine pa so štejele do deset delavcev. Dela in dolžnosti na posameznih delovnih mestih so bile dokaj točno opredeljene, kot je bilo tedaj v navadi, na železnici pa še posebej. V osemdesetih letih je bila fluktuacija delavcev v neposredni proizvodnji, kot smo takrat rekli, izjemno velika. Nemalo delavcev



je vzdržalo v livarni samo po nekaj dni, tako da jih niti spoznati nismo utegnili, kaj šele, da bi si zapomnili njihova imena in priimke. Tedaj so imeli zaposleni na železnici namreč proste karte, ki so veljale po celi Jugoslaviji, in tako je bilo v livarni zaposlenih kar nekaj delavcev celo iz Negotinske krajine (med sabo so se sporazumevali v romunskem jeziku). Nekateri še danes živijo v Ljubljani. Sicer pa je bila livarna Jugoslavija v malem. In ker so delavci po vikendih prihajali na delo pogosto z nočnimi vlaki z nedelje na ponedeljek, so garderobe ob ponedeljkih, bolj kot ne, spominjale na Kosovo polje po bitki, proizvodni rezultati pa so bili temu primerni. In če k navedenemu dodamo še to, da so pravoslavni prazniki okoli štirinajst dni kasneje kot katoliški, tem pa prištejemo še muslimanske, dobimo popolno sliko dogajanja. Praznovali pa so se načeloma vsi in praznovali so vsi. Marsikje je še danes tako.

V časih, ko je livarna obratovala vse delovne dni v letu in še kakšnega zraven (tedaj so bile moderne delovne sobote, pa razne solidarnostne delovne sobote itn.), je bil remont navadno enkrat na leto, praviloma junija (kasneje so imeli gospodje vzdrževalci namreč poletne počitnice) in je trajal od petka od 14. ure do naslednjega ponedeljka do 6. ure zjutraj, delalo pa se je vse dni po 12 ur. Postoriti je bilo treba marsikaj, med drugim tudi podreti talilni del kupolk, jih na novo pozidati itd. Zagon

po remontu je bil navadno mučen in poln presenečenj, kar je trajalo še nekaj naslednjih delovnih dni.

Tako kot vzdrževanje je bila tudi nabavna in skladiščna služba organizirana na nivoju Šiške, kar je bilo v tistih časih razumljivo, enako tudi prodaja. Imeli smo tudi svojo skupino električarjev, ki so imeli v livarni tiste čase kar precej posla, kasneje pa so se potrebe tudi na tem področju toliko spremenile (tudi izboljšale), da smo jih poklicali le še takrat, ko je bilo to potrebno.

## PROIZVODNI PROGRAM

Po rekonstrukciji se je velika večina proizvodnje (več kot 90 %) odvijala na liniji z okvirji s svetlim prerezom 400 mm × 500 mm in višino 165 mm. Dimenzija je bila izbrana glede na potrebe železnice po t. i. zavornjakih. To so bili izmenljivi torni vložki, navadno na vsakem kolesu po dva, pa tudi več, dolgi so bili od 200 mm do 450 mm, večinoma s prerezom 65 mm × 80 mm in so imeli zelo različno geometrijo. V okvirjih so bili od enega do štirje ulitki s skupno maso med 20 kg in 35 kg. Glavnina proizvodnje v osemdesetih letih je bila pet tipov zavornjakov v skupni količini okoli 200 000 kosov letno (+/-). Pri ročnem formanju so bile serije bistveno manjše, letno pa se je v proizvodnji zvrstilo okoli 300 pozicij za najrazličnejša podjetja, ki so se ukvarjala s strojegra-



**Slika 5.** Izdelki Železniške livarne v Šiški na sejmu v Beogradu (v 80. letih prejšnjega stoletja)

dajo: SCT, Gradis, Itas, Mlinostroj, Elan, IMP, Turboinštitut, Litostroj, Iskra itn. Najtežji ulitki so tehtali do dve toni (kobilice za Elanove barke, pa tudi sicer se je za to tovarno veliko ulivalo – predvsem razne uteži za dviganje. Zadnja velika pošiljka – 60 t – je šla v Libijo). Predvsem po zaslugi Litostroja – Tovarne črpalk pa so naši izdelki raztreseni po vsem svetu (slika 5).

## LITINA

Osnovno sestavo litine je določal jugoslovanski, kasneje pa evropski železni-

ški (UIC) standard. Razlika je bila le v tem, da se je količina fosforja z leti dvignila z 0,8 % na 1 % (s tem pa tudi torni količnik in posledično vse drugo). Ogljika je bilo okoli 3,3 %, silicija okoli 2,0 %, mangana med 0,5 % in 0,8 %, žvepla okoli 0,1 % in bakra približno 0,3 %. Povprečna trdota litine je bila 180 HB, s povišanjem masnega deleža fosforja pa 210 HB. Načeloma smo se držali v bližini  $Sc = 1$ . Natezna trdnost take litine je bila okoli  $245 \text{ N mm}^{-2}$ , kar je tudi za splošno strojogradnjo povsem zadoščalo, pa tudi obdelovalnost je bila praviloma odlična (razen v nekaterih redkih, zelo specifičnih pri-

merih). Ulivali smo tudi zavornjake s povečano količino fosforja (2,5 % in s tem višjim tornim koeficientom) za Hrvaške železnice. Tam so namreč na nekaterih odsekih začeli voziti z višjimi hitrostmi, zaustavna oziroma zavorna pot pa je morala ostati enaka.

Nekoč so imeli v naši livarni navado, da so ob koncu taljenja pripravili t. i. strojno litino (brez fosforja) in z njo ulivali razne izdelke za zunanje naročnike, ostanek pa zlili v forme z zavornjaki. Rezultati pri zaviranju s takimi zavornimi vložki niso bili spodbudni (pri prenizkem fosforju namreč zavornjaki radi »zaribajo«, treba je bilo ponovno stružiti kolesa, njihova trajnostna doba se je skrajšala itd.), zato se je ta praksa ukinila, naročnike pa obvestilo, da je na voljo le še »železniška« litina. Praktično ni bilo nikogar, ki bi ga ta sprememba motila iz takih ali drugačnih razlogov. Naj še omenimo, da je »železniška« litina korozijsko relativno dobro obstojna, nepeskana pa skoraj povsem.

## SUROVINE

Osnovni surovini vsake sive livarne sta, ob stari litini seveda, koks in surovo železo, poleg njiju pa še kvaliteten kremenov pesek ustrezne granulacije in bentonit. Koks smo nekoč dobivali iz koksarne v Lukavcu (z leti je bil vedno boljši), kasneje iz Bakra (uvoz iz Bra-

zilije), na koncu pa smo ga nabavljali prek podjetja TERMO iz Škofje Loke (v bistvu je bil iz vseh vetrov, vendar kvaliteten). Vmes je bilo nekaj epizod s češkim in poljskim koksom. Zlasti slednji nam je povzročal silne preglavice, saj žlindra ni in ni hotela iz peči. Je bil pa poceni. Podobno je bilo s poljskim grodljem, kjer so se pojavljali še nekateri nenavadni dodatni problemi v strukturi, in sicer pod površino ulitkov in na njej. Navadno smo dobivali grodelj iz Vareša in nekaj iz Štor, občasno kako pošiljko iz Rusije, Češke in še od drugod. Zadnja leta smo vse surovo železo kupovali pri že omenjenem Termu, kjer izdelujejo kameno volno in imajo v bistvu obrnjen proizvodni proces kot v sivih livarnah. Njih zanima žlindra, ki jo predejo in naprej predelujejo v izolacijske materiale, surovo železo pa je za njih odpadek. V našem primeru je ta odpadek koristen, saj ima precej fosforja in silicija, tako da smo dodajali potrebne ferolegure praktično le za korekcijo kemične sestave. Težavo smo imeli le s tem, da so pol leta v Škofji Loki pretaljevali amfibolit (Avstrija), potem pa diabaz (Hrvaška), surovo železo iz obeh talin pa je bilo na istem kupu, vendar z zelo različno kemično sestavo.

Bentonit nam je desetletja dobavljala INA, Kutina, (prav tako livarsko črnilo – inakol) in na kvaliteto nismo imeli pripomb. Vmes je bilo le nekaj kratkih epizod z bentomakom (Makedonija), ki

pa se ni najbolje izkazal (prevelik raztros in relativno slaba tlačna trdnost).

Prvotno so se v naši livarni uporabljali peski podjetja KREMEN, Novo mesto, s povprečno zrnatostjo 0,16 mm in z, za naše potrebe, ne najboljšo prepustnostjo. Ker je bil povprečen perlitni rob na ulitkih debel okoli 0,2 mm, v primeru zavornjakov pa je bilo zeleno, da elementarni ogljik, ki je izločen v litini v obliki lističev oziroma rozet, pri zaviranju čim prej začne mazati, smo prešli na moravški pesek, in sicer na frakcijo s povprečno granulacijo 0,25 mm, da je bila površina ulitkov primerno valovita. Ko so pri TERMITU v Moravčah dokončno uredili separacijo in je bila mogoča dostava sušenega peska s cisterno, smo se rešili marsikateri skrbi in nadležnega ročnega prekladanja. Tudi pri proizvodnji kalupov za termitno varjenje tirnic smo prešli na moravški pesek, potem ko je licenčna pogodba s podjetjem Elektrotermit, Essen, potekla (prej smo pesek na njihovo zahtevo vozili iz Lipika, Hrvaška). Le oljna jedra za zavornjake smo še naprej izdelovali z novomeškim peskom – delež neizprane gline nam je v tem primeru prišel kar prav. Površina lukenj v ušesih zavornjakov, skozi katere se zabije vzmetna zagozda, ki drži zavornjake na nosilcu, in so izdelane s takimi jedri, je zelo gladka, čeprav smo jedra, če se je mudilo, v te namene izdelovali tudi po CO<sub>2</sub>-postopku in z moravskim peskom. Z vodnim steklom za

ta postopek in z raznimi dodatki za razpad jeder po litju so bile ciklične teža-ve, ne glede na to, kje smo ga naročali in v kakšni embalaži je bil. Včasih smo pa tudi sami kaj dodali.

Z leti nam je uspelo doseči, da so se izrabljeni zavornjaki vračali v livarno (ti imajo povprečno še tretjino mase in so bili za nas optimalen in cenovno najugodnejši vložek). Potrebno staro litino smo dobivali prek Surovine in Dinosa. Ker se njim tedaj to še ni zde- lo potrebno, smo jo lomili sami ali v razbijalnici, ali na posebni hidravlični preši (zavorne bobne npr.), ali na roko s težkimi kladivi.

Ferolegure smo nabavljali večinoma v domačih logih in gajih (Eksoterem, Termit), z izjemo ferofosforja, ki smo ga dobivali iz Avstrije.

## CENE

Tiste čase so se povprečne cene zavornjakov (tudi evropske) navadno gibale okoli ene nemške marke za kilogram (približno pol današnjega evra). Ulitke, ki smo jih formalno ročno, smo prodajali trikrat dražje, pa tudi več, če je bil kos bolj kompliciran (npr. rotorji za centrifugalne črpalke). Ceno smo določali za vsak ulitek posebej, glede na potrebno vloženo delo, serijo itn.

Po zaprtju naše livarne leta 2003 je začela železnica kupovati zavornjake v Italiji (Fonderie Pisano, Salerno). Itali-

jani so prej kot v letu dni dosegli povišanje cene približno za petino, kasneje pa še precej več. Kasneje se je cena umirila na okoli 1,2 EUR/kg. Mi smo tak razvoj dogodkov tako ali tako predvideli glede na vse, kar se nam je dogajalo v tistih letih. Koliko so se stroški železnici z zaprtjem livarne povečali, se da izračunati brez posebnih težav. Letna poraba zavornjakov v Sloveniji je okoli dobrih tisoč ton. (Podobno pot kot izdelava zavornjakov je šla že pred leti izdelava kalupov za termitno varjenje tirnic in še kaj.)

Prodaja Livarne je bila v letu 1995 756 572 EUR (181 305 000 SIT), od tega zavornjaki 1378 t oz. pribl. 684 500 EUR (164 mio. SIT), ročno formanje 56 t oz. pribl. 684 360 EUR (15 mio. SIT), obloge za termitno varjenje tirnic 4731 parov oz. pribl. 62 593 EUR (2 mio. SIT). Zaloga je s 15 t narasla na 140 t. Celotna proizvodnja je bila tako v tem letu 1580 t.

V tem letu nas je bilo v Livarni zaposlenih 35 delavcev, dobrega pol leta pa smo imeli še dva zaposlena prek biroja

**Tabela 1.** Nabava materialov in drugi stroški Livarne v letu 1995

Vrsta blaga oz. storitve	Količina	Cena/SIT	Znesek/SIT	Znesek/EUR
Koks	362 t	29,97	10 862 926	63 900
Surovo železo (termo)	170 t	19,90	3 383 000	19 900
Surovo železo (uvoz)	21 t	24,40	512 400	3 014
Stara litina	470 t	17,31	8 133 040	47 841
Zavornjaki (povrat)	608 t	18,84	11 454 720	67 381
Masa Natural (poprav. peči)	83 t	13,46	1 117 180	6 572
Masa NMG 3	19 t	21,56	415 676	2 445
Bentonit	48 t	26,49	1 271 520	7 480
Inakol (liv. črnina)	1 t	20,05	20 050	118
Ferosilicij	12 t	65,46	785 520	4 621
Ferofosfor	6 t	333,92	2 003 520	11 785
Visk	12 t	130,77	1 582 317	9 308
Armature			13 379 079	78 700
Elektrika	400 000 KW	22,82	9 128 000	53 694
Odvoz smeti	250 kont.	7000,00	1 750 000	10 294
Plače v Livar			40 000 000	235 294
Investicije (rešetka)			900 000	5 294
Analize	460	8000,00	4 140 000	24 353
Mestno zemljišče			1 000 000	5 882
Razno			15 000 000	88 235
<b>S K U P A J</b>			<b>126 839 027</b>	<b>746 112</b>

za delo. Promet na zaposlenega v Livarni je bil okoli 35 000 EUR.

V tabeli 1 je prikazana nabava materialov in drugi stroški Livarne v letu 1995.

### KONTROLA KVALITETE

Kemijske in mehanske lastnosti naših litin so desetletja preiskovali v litostrojskih laboratorijih, prav tako metalografijo, in to v skupno zadovoljstvo. Vzorce smo dostavljali v Litostroj enkrat tedensko – za vsak delovni dan, ko se je ulivalo po enega. Sprva smo žagali naključno izbrane zavornjake, ki so šli v izmet, npr. zaradi porušene geometrije, in na njih opravili vse potrebne raziskave, redno tudi metalografske (zanimala nas je predvsem debelina perlitne plasti na robu ulitka, razporeditev grafita itd.). Ko so se pojavili kvantometri, smo na vsak delovni dan, ko se je ulivalo, pripravili po en vzorec za kemično analizo na tej napravi in po en vzorec (razrezan zavornjak) na teden za druge raziskave. Če je kvaliteta zanihala, so bile raziskave seveda pogostejše, kar pa je bilo le redko potrebno. Po potrebi so nam v Litostroju izdali tudi ateste, saj so bili za to pooblaščen. Posel je bil dodobra utečen, osebje laboratorijev pa seznanjeno tudi z našo problematiko, in če je bilo treba, so nam šli zelo na roko. Eno takih področij je bilo ulivanje zavornjakov

s povišanim fosforjem. Zadnja leta je šel razvoj preiskovalnih metod že tako daleč, da smo lahko imeli rezultate kemijske analize v obratu že v dobri uri po ulitju (vmes je bilo treba vzorce za kvantometer dostaviti v Litostroj). Razumljivo je, da smo večkrat razmišljali o svojem laboratoriju, vendar se nam račun nikakor ni hotel iziti. In smo ostali pri storitvah Litostroja – kot že povedano – v skupno zadovoljstvo.

Pač pa smo v livarni izvajali dnevno obratno kontrolo, tako vizualno kot tudi trdote ulitkov, mehanskih lastnosti zavornjakov (padalno kladivo) in peskov. Laboratorij za peske je imel letnico izdelave 1955 in je bil izdelan v Budimpešti po licenci Georga Fisherja. Prvih trideset let je srečno prebil v skladišču, ker očitno ni bilo nikogar, ki bi hotel ali znal delati z njim. S prihodom novih moči v proizvodnjo smo ga aktivirali, izdihnil pa je skupaj z livarno (aparatura za merjenje tlačne in strižne trdnosti livarskega peska, peč za določitev točke sintranja pa že mnogo prej).

V zvezi s problematiko »zaribavanja« železniških koles pri zaviranju je bilo napravljenih več raziskav (prof. I. Kosovinc) brez jasnih odgovorov, ker jih dejansko tudi ni moglo biti. Vzrokov tovrstnih poškodb je namreč lahko več: od povsem subjektivnih (premočno zaviranje ali prehitro speljevanje) do bolj ali manj objektivnih – npr. okvar na avtomatiki pnevmatskih zavornih

naprav itn. Rezultat je bil v večini primerov enak: Kolo se začne v pasu, kjer je najbolj obremenjeno, to je tam, kjer teče po tračnici, topiti (navadno je ta pas širok okoli 20 mm), staljen material pa se odlaga na zavornjaku v tankih lističih, debelih od 0,1 mm do 0,2 mm. Pri nadaljnjem zaviranju prihaja do trenja enakih materialov, ki nujno preide v tornu taljenje, seveda spet kolesa, ker je napetostno bistveno bolj obremenjeno kot zavornjaki. Problematika je kompleksna, rešitev navadno zapletena, če sploh je, in so si na železnici domislili genialne rešitve: dežurnega krivca. Nenadoma so bili za vse take poškodbe krivi nekvalitetni zavornjaki oziroma livarna. Na srečo so tako rekoč vse ekspertize, ki so bile opravljene v zvezi s to problematiko, ugotavljale, da je z zavornjaki vse v najlepšem redu in da je treba vzroke za navedene poškodbe iskati drugje. Načeloma pa je treba vsak tak primer obravnavati individualno.

Sicer pa so bili atesti uporabljenih materialov in naših izdelkov arhivirani za desetletja nazaj, vsak zavornjak pa je imel ulit datum izdelave.

## TEHNOLOGIJA

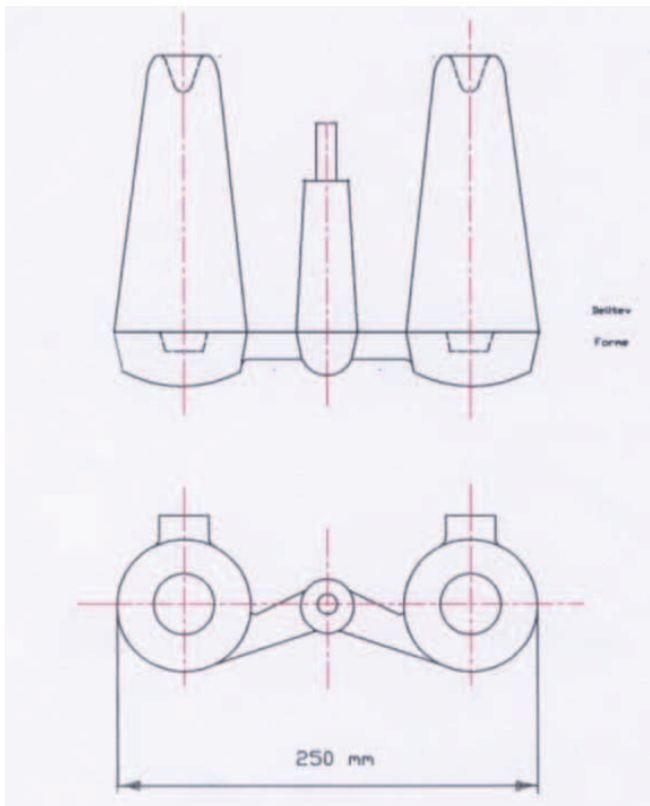
Na liniji smo uporabljali enotni pesek s povprečno zrnatostjo 0,25 mm, le izjemoma tudi bolj finega, modelnega, kadar in če je bilo to potrebno (npr. za pekače!). Večina jeder je bila izdelana

iz oljnega peska (z raznimi dodatki – interna receptura) ter pregreta in ohlajena pred vlaganjem v forme. Jeder, izdelanih po CO<sub>2</sub>-postopku, smo na liniji uporabljali malo ali čim manj iz znanih razlogov. Drugače je bilo pri ročnem formanju, kjer smo zadnja leta uporabljali skoraj izključno le CO<sub>2</sub>-jedra. Ne tako daleč nazaj je bila izdelava jeder zapleten postopek, ki je zahteval obilo prakse in velike peči, kurjene z drvimi in premogom oz. koksom. V naši livarni smo tak način dela opustili sredi osemdesetih let, v pečeh pa smo imeli skladišča modelov in materiala.

Z leti je pri ulivnih sistemih prišlo do neprimernih ali celo škodljivih poenostavitvev. Marsikdaj se je ulivni kanal opustil, saj je bila tako forma hitreje izdelana (včasih pa tudi prostora ni bilo). Ulivalo se je v takem primeru direktno v napajalnik, ki je bil navadno tudi predimenzioniran. In če livarji tudi nosu ponovce niso dobro očistili (uprabljali smo ponovce s sifonom, pred tem pa navadne lonce), kar ni bilo tako redko, so bili rezultati pričakovani – prevelik izmet oziroma potrebna popravila. S prstom se je kazalo drug na drugega in je bilo zato včasih v poslovodski pisarni že kar precej vroče. Eden od razlogov je bil brez dvoma ta, da so bili livarji glede na druge delavce v podjetju relativno slabo plačani in precej več so morali delati (interna norma v obratu je bila okoli ene tone premetanega materiala na uro dela).

Sredi osemdesetih let je bila situacija v livarni taka, da se je en mesec delalo, da se je pokrila izmeta (oziroma je bila količina izmeta identična z mesečno proizvodnjo), zastojev zaradi okvar je bilo tudi za kak mesec, bolniške so bile tako posebno poglavje, pritiski za povečanje proizvodnje pa veliki. Celó v Italijo naj bi začeli izvažati zavornjake. Z Italijo, hvala bogu, ni bilo nič, ker bi si obratovodstvo v tedanjih razmerah s tem poslom zelo verjetno polomilo zobe.

Zmanjšanja izmeta smo se lotili tako, da smo začeli dnevno kontrolirati livarske peske (previsoke vlage niso bile nobena redkost) in s postopno zamenjavo ulivnih sistemov, in sicer s takimi, ki so onemogočali, da bi žilindra kakor koli prišla v ulitke. Pri ročnem formanju smo izdelali elemente ulivnega sistema (sestavljali smo jih skoraj kot lego kocke). Zopet se je ulivalo skozi ulivni kanal, iz njega je litina tangencialno pritekla v napajalnik, ki se je v tem primeru rabil kot centrifuga



**Slika 6.** Ulivni sistem s centrifugalnimi napajalniki – za zavornjaka od  $2 \times 10$  kg na kos do 13 kg na kos



za odstranjevanje žlindre, in se prelila v livno votlino (slika 6). Po končanem litju se je napajalnik posulo z livarskim peskom, leta kasneje pa z eksotermnim posipom, kadar je bilo to potrebno ali pa se je sploh uporabilo zaprte napajalnike. S pojavom keramičnih filtrov smo začeli uporabljati tudi te, vendar le pri ročnem formanju. Uporabljali smo jih v primeru, ko napajalnik ni bil potreben in pri zelo zahtevnih ulitkih.

Pri velikoserijski proizvodnji smo se najprej lotili tistih modelnih plošč, kjer je bilo največ izmeta, seveda. Navadno je bilo treba plošče samo poravnati, sicer pa izdelati nove (uliti, žariti, obdelati). Modeli so bili večinoma bronasti, pa tudi naša »železniška« litina se je v te namene odlično obnesla, le nekoliko bolj krhka je bila. Navadno sta bila v formi po dva ulitka zavornjakov (včasih trije – dva vzporedno, tretji prečno). Ulivali smo skozi ulivni kanal, ki je bil na vrhu razširjen, kar smo napravili s t. i. vzmetno glavo, ki se je nasadila na nastavek za ulivni kanal pred formanjem, po njem pa se je izvlekla iz forme. V spodnjem delu forme se je ulivni kanal razcepil na dva dela, vsak kanal pa je litino dovedel v napajalnik tangencialno. Tu se je litina pri ulivanju zavrtela, nato pa prelila v livni votlini (od tod pa lahko še v tretjo, če je bila taka razporeditev na plošči). Napajalniki so bili zaprti in konični, saj so se rabili tudi kot kompenzator za sunke, ki lahko dvignejo zgornji del

forme in nastanejo v trenutku, ko se livne votline zapolnijo (ferodinamični tlaki, ki so lahko seveda bistveno večji od ferostatičnih). Napajalnik je imel v naši livarni torej trojno vlogo: svojo osnovno, v njem se je litina očistila in kompenziral je sunke, ki nastanejo pri polnjenju forme z litino (avtor podpisani). Seveda do končnih rezultatov nismo prišli takoj. Malo se je računalo, malo žgalo ulitke in ulivne sisteme, pa malo spremenilo ali dopolnilo itn. Vsak ulitek oziroma vsaka konfiguracija na modelni plošči ima namreč svoje zahteve. Kjer je bilo mogoče, smo tak ulivni sistem uporabili tudi v ročni formariji (namesto filtrov, ki kljub vsemu pomenijo strošek).

Prvotno se je ulivalo tako, da je zavornjak »ležal« v formi (z ušesom navzdol), kar je bilo ugodno tudi zato, ker se je laže vložilo jedro in armatura (To je navadno, očiščeno železo, večinoma z dimenzijami 5 mm × 20 mm in poljubno dolžino, ki preprečuje, da zavornjak ob eventualnih udarcih, ki se pojavljajo pri eksploataciji, razpade. Armature so lahko včasih zelo komplicirane, posebno pri visokofosfornih zavornjakih). Težava pa je bila v tem, da so se vse eventualne napake nakopičile v zgornjem delu forme oziroma na »delovni« ploskvi zavornjaka – torej tam, kjer je to v našem primeru najmanj primerno. To je bil tudi razlog, da smo vse zavornjake od tedaj naprej ulivali z ušesom, jedrom in armaturo v zgor-

njem delu forme. Našo livarno smo sicer zaprli, modelne plošče za izdelavo zavornjakov pa prodali, in menda še vedno »laufajoz« nekje v Srbiji (baje v Užicu). Sicer pa je bila naša livarna po splošnem mnenju najboljša za izdelavo zavornjakov v Jugoslaviji (v naši bivši državi se je tedaj letno porabilo med 10 in 15 tisoč tonami zavornjakov; mi smo jih ulili 3 tisoč).

### VZDRŽEVANJE IN IZBOLJŠAVE

Vzdrževanje mehanizacije in razna popravila so nam vzeli veliko časa, truda in energije, saj praktično ni bilo dneva, da ne bi kje kaj zaškripalo oziroma se pokvarilo. Vzroki so bili včasih prav banalni, npr. slaba ali nikakršna higiena pri vzdrževanju. Zato smo vse stroje, preden so šli v popravilo, najprej temeljito, oziroma kolikor se je le dalo, oprali. Ležaj na disku za izmetavanje peska iz mešalnika, na primer, nam je v povprečju vzdržal tri tedne, zamenjava pa ni bila nič kaj prijetno opravilo. Toliko časa smo se ukvarjali s tem problemom, da smo na koncu menjavali samo še diske, pa še te le zelo redko, rezervni ležaji pa so nabirali rjo in prah v skladišču. Pa sploh niso bili poceni! Na splošno smo si poskušali sami pomagati, če se je le dalo. Tu nam je bil v veliko pomoč tako rekoč genialni str. tehnik Franc Turk, ki je marsikatero napravo malone sam izumil, pa ne samo v livarni, temveč tudi

po drugih obratih tedanjega Podjetja za vzdrževanje voz in strojev v Šiški, ki je delovalo v okviru železnice (ŽG). Eden takih dosežkov je konstrukcija premičnega podvozja na traktorjih, ki omogoča vožnjo tudi po tirih in s tem premik železniških vozil v okviru podjetja, čiščenje snega po tirih itd. Tako opremljenih traktorjev smo v Šiški izdelali nekaj deset (in se še izdelujejo), svoj delež pa je tu prispevala tudi livarna. Vse te izboljšave so med drugim privedle do tega, da je bila našemu podjetju podeljena plaketa zlato sonce, ki je bila za časa Jugoslavije najvišje priznanje za inovativne dosežke. Seveda brez razumevanja tedanjega vodstva podjetja za naše eksperimente (ki niso bili vedno uspešni), nam ne bi uspelo kaj dosti napraviti; zasluga gre zlasti inž. Ivanu Mediču.

Livarna je v tistem času dobila nov nadstrešek na južni strani, kjer smo imeli skladišče ulitkov, potem novo skladišče za ferolegure in druge materiale, ki smo jih potrebovali pri vsakdanjem delu, ter za rezervne dele. Livarna je tedaj dobila tudi novo kritino, saj je stara že izdatno puščala na vseh koncih in krajih. To je bil tudi edini resnejši gradbeni poseg v samo stavbo livarne v vsej njeni zgodovini. Prekrivali pa smo seveda – le kdaj neki? Sredi decembra, med snežnimi meteži in v hudem mrazu. Ob razkriti strehi je spodaj v livarni tekla proizvodnja, delavci smo kihali, kaj hujšega pa na srečo le ni bilo.

Sicer pa so marsikatera opravila v zvezi z livarno tako ali drugače v vsej njeni zgodovini potekala pod vedrim nebom, v snegu in dežju, na pripeki ali mrazu – tako priprava vložka, ki je bila do zadnjega skoraj povsem ročno opravilo, transport okoli livarne in še marsikaj. Livarna je bila tudi zadnji obrat v Šiški, ki je dobil centralno kurjavo, pa še to ne v celoti. Tako rekoč za vsak posamezen radiator se je bilo potrebno boriti. Vsa prepričevanja, da se z zmrznjenim livarskim peskom ne da delati, niso kaj dosti zalegla. Podobno je bilo s transportnimi potmi. Še sredi osemdesetih let so bile okoli livarne tako rekoč povsod same jame, luže in blato, pa tudi v sami livarni tlaki marsikje niso bili urejeni. Dokazovanje in prepričevanje, da je daleč največ transporta v podjetju v livarni in okoli nje, je dalo rezultate šele čez leta. Zadnje površine smo zabetonirali šele neposredno pred zaprtjem, in sicer lastnoročno delavci livarne. Kaj hočemo. Tako je, žal, bilo. Borili smo se do zadnjega diha ... Nekateri v vodstvu železnice pa so se zadovoljili s tem, da so nam z užitkom metali polena pod noge. Čim več, če je le bilo mogoče!

## EPILOG

Prav neverjetno je, s čim vse so nam grenili življenje. Na vse mogoče načine so skušali doseči, da se livarna zapre. Eden od teh načinov je bil tudi ta, da je

bil objavljen javni razpis za dobavo zavornjakov, in to kljub temu, da je imela železnica svojo livarno! Po nekaj poskusih oziroma razpisih se je končno našel pravi dobavitelj: Fonderie Pisano iz Salerno v Italiji. Tja je nemudoma odhital tedanji direktor železniškega Centra za nabavo s svojo sodelavko, kasneje pa še najmanj ena veččlanska delegacija. Obratovodjo Železniške livarne za vsak primer niso povabili s seboj. Lahko bi se kaj zakompliciralo!

Med tem v livarni nismo sedeli križem rok. Čim so nam prišli v roke prvi kosi zavornjakov iz Italije, smo jih temeljito pregledali in dali v analizo. Rezultati so bili tako glede geometrije kot kemije negativni. Da ne govorimo o tem, kaj bi napravili z nami, če bi v našem obratu izdelovali take zavornjake! Tako pa vse tiho je bilo. Nesreča v livarni je prišla kot naročena. Livarno smo zaprli in posel teče nemoteno dalje.

Na pobudo ravnatelja Železniškega muzeja Mladena Bogiča smo o delu v livarni posneli okoli štiri ure filmskega materiala. Nekatere kadre smo posneli samo poskusno, ker pa nas je nesreča prehitela in jih ni bilo mogoče ponovno posneti, so bili v filmu uporabljeni. Na digitalno kamero je tedanje dogajanje posnel in potem gradivo zmontiral, opremil z glasbo, zvokom in nekaterimi komentarji Primož Ozvald. Avtor je po poklicu strojni inženir, sicer pa velik ljubitelj železnice.

Enourni film je marsikomu zelo všeč in je odličen dokument vsakodnevnega utripa v livarni in dogajanja ob njenem zapiranju.

Zadnje dni smo v livarni, poleg podpisanega, preživeli:

- Franko Barukčič, talilec, livar, brusilec, strojni formar,
- Šimo Barukčič, strojni formar, brusilec, kovač, polnilec kupolk,
- Jozo Deronja, talilec, livar, voznik viličarja, delavec na čistilnem stroju, brusilec, strojni formar in še kaj,
- Gojko Gostimirovič, strojni formar, izdelovalec jeder in armatur, pripravljavec peska,
- Marijan Horvat, strojni formar, izdelovalec armatur, odgovoren tudi za kurjenje in zalaganje kupolk,
- Marjan Ihanc, strojni in odličen ročni formar (veliki ulitki),
- Jožko Jesenovec, delavec pri rešetki in v čistilnici, nabavljavec malice,
- Andrija Jurič, pripravljavec peska, strojni formar, odgovoren tudi za dvig okvirjev na konvejer ter za rešetko,
- Ivanka Križelj, administratorica,
- Tomo Lapornik, strojni formar, izdelovalec armatur, odgovoren tudi za zalaganje kupolk, sicer pa po poklicu strugar in strojni tehnik,
- Marko Mavec, strojni in ročni formar,
- Tone Novak, skupinovodja, strojni formar, jedrar, izdelovalec armatur,

- Andrej Obreza, vzdrževalec,
- Blaž Perkovič, talilec, livar, brusilec,
- Iztok Petrle, izjemno agilen poslovodja, skladiščnik in nasploh »deklica za vse«,
- Milenko Petrovič, livar, voznik viličarja, delavec pri čistilnem stroju, brusilec, zalagalec kupolk,
- Nada Pranjic, jedrarka,
- Zoran Simić, pečar, livar, strojni formar, brusilec, zalagalec kupolk,
- Aleš Skopec, vzdrževalec, orodjar, odgovoren tudi za dvig okvirjev na konvejer ter za rešetko,
- Drago Slijepčević, odgovoren za dvig okvirjev na konvejer, izdelovalec armatur, strojni formar,
- Alojz Štupar, pečar, strojni formar, brusilec, zalagalec kupolk, izdelovalec armatur,
- Pero Tokić, pečar, livar, brusilec, zalagalec kupolk in
- Miodrag Zdravković, talilec, livar, brusilec, zalagalec kupolk.

## IN DANES ?

Stavba Livarne še stoji. Stroje in razno opremo se je prodalo, če je le bilo mogoče. Konvejer in pripravo peska so razrezali in prodali na odpad, prav tako livarske formarske stroje (foromate). Pisarne so deloma izropali, pohištvo, kar ga je ostalo, je šlo v Moste, dokumentacija Livarne skupaj z arhivom pa v kontejner.

Pod kupolko, s katero smo talili zadnji dan, smo pustili podložni koks in na žlebu žlindro. Druga kupolka pa je še vedno pripravljena za taljenje, le prižgati jo je treba.

Izdelavo raznih ulitkov, ki smo jih nekoč izdelovali za potrebe železnice, pa tudi nekaj drugih pozicij je prevzel nekdanji poslovodja v Livarni Jani Kopač in jih sedaj izdeluje v svoji livarni v Vikerčah pod Šmarno goro (ohišja za pritlikave signale, razne rezervne dele za lokomotive, vagoni itn.).

Za stavbo Livarne se zanima Tehniški muzej Slovenije, saj naj bi v njej uredil avtomobilski oddelek, enako se zanima tudi za bivšo upravo, da bi tja preselil svojo. Skupaj z Železniškim muzejem, ki že domuje v Šiški, in nekaterimi obrati, ki so še v uporabi – recimo kovačijo, bi tako na prostoru

nekdanjega Podjetja za vzdrževanje voz in strojev v Šiški lahko dobili lep, zanimiv in zaokrožen muzejski kompleks.

Prispevek je posvečen prelitemu znoju livarjev v Železniški livarni v Šiški.

## VIRI

Arhiv Železniške livarne v Šiški

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Reisp, B. (1987): Korespondenca J. V. Valvasorja z Royal Society, SAZU

Rustja, K.: Članki na temo zgodovine železnice, posebej delavnic v Šiški, objavljeni v več številkah in letnikih revije Nova proga

Skupina avtorjev (1972): Metalurški priročnik, TŽS

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Struna, A. (1955): Vodni pogoni na Slovenskem, TMS



## **Društvo alumnov diplomantov Oddelka za materiale in metalurgijo**

Tradicija ohranjanja stikov med diplomanti in Oddelkom za materiale in metalurgijo (OMM) traja že vrsto let in seveda ni namenjeno le obujanju spominov na študijska leta, temveč tudi zagotavljanju poklicne strokovne in karijerne povezanosti, izmenjavi dobrih praks med diplomanti, študenti in OMM, hkrati pa predstavitev uspešnih posameznikov, ki s svojim delom dvigujejo tudi ugled izobraževalne institucije, kjer so pridobili izobrazbo.

**Na ustanovnem občnem zboru 23. 10. 2012 je bilo ustanovljeno Društvo alumnov OMM – društvo diplomantov Oddelka za materiale in metalurgijo Naravoslovnotehniške fakultete Univerze v Ljubljani.**

Z ustanovitvijo Društva alumnov OMM želimo stakati trdne vezi med študenti, diplomanti in prijatelji OMM. Njegove dejavnosti bodo:

- vzpostaviti in negovati povezanost in komunikacijo kot krepitev vezi med diplomati vseh generacij;
- negovati pripadnost diplomantov šoli;
- aktivno sodelovanje pri razvoju metalurške stroke;
- promocija dosežkov članov društva;
- prispevati k večji prepoznavnosti diplomantov tako doma kot v tujini, v javnem in zasebnem sektorju;
- ustvarjati in spodbujati sodelovanje med člani Društva alumnov OMM in gospodarskimi subjekti ter drugimi družbenimi institucijami;
- zagotoviti možnost sodelovanja diplomantov pri razvijanju novih izobraževalnih programov;
- prispevati k osebni in strokovni razvoju posameznikov in organizacij;
- aktivno sodelovanje pri razvoju družbe;
- diplomantom omogočiti druženje in povezovanje.

Delovanje Društva alumnov OMM bo odvisno predvsem od vašega sodelovanja. Mnoge med vami spremlja zgodba o uspehu. Delite jo z drugimi člani kluba ali z bodočimi diplomanti in soustvarjajte njihovo karierno pot. V Društvu alumnov OMM lahko delujete kot predavatelji, vodite okrogle mize, prispevate članek ali novice, pomagate pri organizaciji alumnidogodkov ali sponzorirate alumnidogodke. Vsaka pomoč in ideja bosta dobrodošli. Vaše cenjene

komentarje, predloge in pobude pošljite na:

<http://www.ntf.uni-lj.si/omm/index.php?page=static&item=1225>.



**Slika 1.** Ustanovni zbor Društva alumnov Oddelka za materiale in metalurgijo Univerze v Ljubljani 23. 10. 2012

Članstvo v društvu je prostovoljno.

Član društva lahko postane vsak, ki je uspešno končal kateri koli javno veljavni program izobraževanja, ki ga izvaja ali ga je izvajal Oddelek za materiale in metalurgijo Naravoslovnotehniške fakultete Univerze v Ljubljani ali organizacija, ki je pravni prednik te fakultete. Članstvo v društvu se začne s podpisom pristopne izjave, v kateri podpisnik izjavi voljo, da postane član društva in navede leto diplome, magisterija oz. doktorata ter izjavi, da dovoljuje društvu vpogled v evidenco diplomirancev fakultete. Če iz evidence diplomirancev fakultete ni razvidno, kateri javno veljavni program izobraževanja je končal prijavitelj, odloči o članstvu upravni odbor po izvedenem postopku, v katerem se ugotovi, ali prijavitelj izpolnjuje pogoje za pridobitev članstva.

Društvo ima redne, častne ter pridružene člane.

Člani društva so lahko tudi pravne osebe, ki zaposlujejo diplomante fakultete.

Jožef Medved, Andrej Rosina, Maja Vončina



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**RMZ-MATERIALS & GEOENVIRONMENT** (RMZ- Materiali in geokolje) is a periodical publication with four issues per year (established 1952 and renamed to RMZ-M&G in 1998). The main topics of contents are Mining and Geotechnology, Metallurgy and Materials, Geology and Geoenvironment.

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*\* Additional information and remarks for Slovenian authors:*

*Only Professional papers, Publications notes, Events notes, Discussion of papers and In memoriam, will be exceptionally published in the Slovenian language.*

**Authorship and originality** of the contributions. Authors are responsible for originality of presented data, ideas and conclusions as well as for correct citation of data adopted from other sources. The publication in RMZ-M&G obligate authors that the article will not be published anywhere else in the same form.

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*RMZ-M&G will publish papers of the following categories:*

*Full papers* (optimal number of pages is 7 to 15, longer articles should be discussed with Editor prior to submission). An abstract is required.

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Format of papers in journals:

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ROBERTS, J. L. (1989): Geological structures, *MacMillan, London*, 250 p.

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**Tekst** izpisanega izvoda je lahko pripravljen v kateremkoli urejevalniku. Na disketi, CD ali v elektronskem prenosu pa mora biti v MS Word ali v ASCII obliki.

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<sup>x</sup> University of ..., Faculty of ..., Address..., Country ... (Times New Roman, 11, Center)

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2. by consecutive Arabic numerals in square brackets, superscripted at the appropriate place in the text and arranging the reference list at the end of the text in the like manner; e.g.:  
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This section describes the available data and procedure of work and therefore provides enough information to allow the interpretation of the results, obtained by the used methods.

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This work was supported by the \*\*\*\*.

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- FOLK, R. L. (1959): Practical petrographic classification of limestones. *Amer. Ass. Petrol. Geol. Bull.*; Vol. 43, No. 1, pp. 1–38, Tulsa.

**SECOND OPTION - in numerical order**

- [<sup>1</sup>] TRČEK, B. (2001): *Solute transport monitoring in the unsaturated zone of the karst aquifer by natural tracers*. Ph. D. Thesis. Ljubljana: University of Ljubljana 2001; 125 p.
- [<sup>2</sup>] HIGASHITANI, K., ISERI, H., OKUHARA, K., HATADE, S. (1995): Magnetic Effects on Zeta Potential and Diffusivity of Nonmagnetic Particles. *Journal of Colloid and Interface Science*, 172, pp. 383–388.

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**Key words:** a list of up to 5 key words (3 to 5) that will be useful for indexing or searching. Use the same styling as for abstract.

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“Detailed information about geohistorical development of this zone can be found in: ANTONIJEVIĆ (1957), GRUBIĆ (1962), ...”

“... the method was described previously (HOEFS, 1996)”

ali

2. z zaporednimi arabskimi številkami v oglatih oklepajih na ustreznem mestu v tekstu in z ureditvijo seznama referenc v številčnem zaporedju navajanja; npr.;

“... while the portal was made in Zope<sup>[3]</sup> environment.”

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- CASATI, P., JADOUL, F., NICORA, A., MARINELLI, M., FANTINI-SESTINI, N. & FOIS, E. (1981): Geologia della Valle del'Anisici e dei gruppi M. Popera – Tre Cime di Lavaredo (Dolomiti Orientali). *Riv. Ital. Paleont.*; Vol. 87, No. 3, pp. 391–400, Milano.
- FOLK, R. L. (1959): Practical petrographic classification of limestones. *Amer. Ass. Petrol. Geol. Bull.*; Vol. 43, No. 1, pp. 1–38, Tulsa.

### DRUGA MOŽNOST - v numeričnem zaporedju

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