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ERGONOMIC ASPECTS OF ELECTRIC SHOCK RISK IN THE CONDITIONS OF AN UNDERGROUND MINE

ERGONOMICZNE ASPEKTY RYZYKA PORAŻENIA PRĄDEM ELEKTRYCZNYM W WARUNKACH PODZIEMI KOPALŃ

The risk of electric shock in an underground mine should be considered with regard to ergonomic aspects. Narrow excavations, usually with large amounts of electrical equipment increase the risk of persons on situ making contact this equipment with different parts of the body. The risk of electric shock should be then considered in the context of the possibility of different shock-current paths. An analysis of the effects of an electric current on the human body during an accident caused by touching by any two body points is carried out in the article. A method of calculating factors affecting the severity of the shock by alternating current (a.c.) and direct current (d.c.) has been suggested. These factors describe the different effects of an electric current passing through a human body along the most common paths.

Key words: ergonomics, underground excavations, electric shock risk

Warunki środowiskowe podziemi kopalń należy traktować jako czynnik zwiększający ryzyko porażenia prądem elektrycznym. Ograniczone wymiary wyrobisk podziemnych sprawiają, że trzeba się liczyć z możliwością dotknięcia przez człowieka dowolnymi punktami ciała urządzeń elektrycznych zainstalowanych w tych wyrobiskach. Dotyczy to zarówno elektromonterów obsługujących urządzenia elektryczne, jak i innych osób stykających się z tymi urządzeniami przypadkowo. Skutki przepływu prądu rażeniowego zależą m.in. od drogi jego przepływu. Spośród znanych sposobów oddziaływania prądu elektrycznego na organizm człowieka, jedynie w działaniu na układ krążenia uwzględnia się zróżnicowanie skutków w zależności od drogi przepływu prądu, wprowadzając tzw. współczynnik prądu serca (1) dotyczący kilku najczęściej spotkanych dróg rażenia. Wartości tego współczynnika wg raportu IEC 479-1 (Skutki... 1999) zestawiono w wyróżnionych polach tablicy 1. Analizując działanie prądu elektrycznego na układ krążenia, płynącego wzdłuż innych dróg, zaproponowano pozostałe wartości współczynnika prądu serca (pola niezacieniowane w tabl. 1). Równoważność oddziaływania na układ krążenia przy tych samych wartościach napięcia dotykowego można wówczas określić za pomocą odpowiedniego wskaźnika (11).

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Działanie prądu rażeniowego płynącego dowolnymi drogami na układ nerwowy i tkankę wewnętrzną analizowano przyjmując za punkt wyjścia całkową postać prawa Ohma (4) w polu przepływowym prądu elektrycznego. Pozwoliło to przyjąć założenie, że rozległość drogi przepływu prądu rażeniowego, a więc i jego skutki, są proporcjonalne do sumy spadków napięcia wywołanych prądem rażeniowym w poszczególnych fragmentach ciała. Konsekwencją tego założenia jest przyjęcie definicji wskaźnika charakteryzującego działanie prądu rażeniowego na układ nerwowy i tkankę wewnętrzną, zależnego od rozległości drogi rażenia (12).

Cieplne działanie prądu rażeniowego płynącego różnymi drogami oceniano na podstawie mocy wydzielonej na rezystancji poszczególnych fragmentów ciała, opisanej całkową postacią prawa Joule'a (8). Przy stałej wartości napięcia dotykowego równoważność cieplnego oddziaływania wzdłuż różnych dróg można określić wprowadzając odpowiedni wskaźnik (15).

We wszystkich trzech wskaźnikach równoważności skutków porażenia (11), (12), (15) występują rezystancje poszczególnych odcinków ciała wzdłuż przepływu prądu rażeniowego. Wobec braku jednoznacznych ustaleń w tym zakresie zaproponowano schemat zastępczy ciała człowieka umożliwiający analizę poszczególnych oddziaływań (rys.1b). Uwzględniono w nim znane wartości rezystancji (np. kończyn) i przypisano dodatkowo porównywalne wartości rezystancji wzdłuż dróg dotąd nie rozpatrywanych w literaturze (10), kierując się m.in. specjalnym znaczeniem jakie odgrywają organy zlokalizowane w klatce piersiowej i w głowie.

Znając wartości poszczególnych wskaźników zaproponowano wypadkowy wskaźnik stopnia (lub ciężkości) porażenia (17) charakteryzujący łączne oddziaływanie prądu płynącego wzdłuż różnych dróg. Wobec braku możliwości doświadczalnego zweryfikowania słuszności przyjętych współczynników wagowych, przedstawiono trzy wersje wypadkowego wskaźnika stopnia porażenia, eksponujące: działanie na układ krążenia (18), działanie na układ nerwowy i tkankę wewnętrzną (19) oraz łącznie obydwa działania (20).

Obliczeniowe wartości poszczególnych wskaźników zestawiono w tablicach 2 i 3, natomiast względne wartości wypadkowych wskaźników odniesione do drogi lewa dłoń-obydwie stopy (Dl-SS), obliczone według wzoru (21) — w tablicach 4 i 5.

Stopień porażenia prądem elektrycznym jako element składowy ryzyka wypadków elektrycznych, do których dochodzi w podziemiach kopalń, należy rozpatrywać w kontekście czynników ergonomicznych wynikających ze specyfiki warunków środowiskowych w miejscu pracy. Wyrazem udziału tych czynników jest m.in. możliwość porażenia prądem elektrycznym przepływającym dowolną drogą przez ciało człowieka.

Zaproponowane w artykule wypadkowe wskaźniki stopnia porażenia umożliwiają uwzględnianie różnorodnych oddziaływań prądu na organizm, zróżnicowanych w zależności od drogi przepływu prądu. Wskaźniki te mogą być pomocne przy ocenie ryzyka porażenia prądem elektrycznym na różnych stanowiskach pracy w podziemiach kopalń.

Słowa kluczowe: ergonomia, wyrobiska podziemne, porażenie prądem elektrycznym, ryzyko

1. Introduction

Risk-assessment is a basic task for a safety management system. Risk is the combination of the probability of an accident's occurrence and severity of its outcome. Estimation of the seriousness of accidents caused by electric shock should take into consideration the patho-physiological changes that take place in the body, which depend, among others, on the path of the shock-current.

Most underground excavations, especially near working faces or those being prepared for operation, are of small dimensions. This increases the chances of the metal housings of electrical equipment (exposed conductive parts) and rocks or metal structures which are not part of electric equipment (extraneous conductive parts) being touched by a man simultaneously. This applies to virtually all persons present at faces. Additionally, people who are responsible for the maintenance of electric equipment may be at risk of making contact with live electric equipment*. At certain voltage level there is a probability of contact occurring leading to electric shock, it being likely that the current will pass via different routes.

An analysis of the anticipated severity of the electric shock has been carried out in the article and conventional factors of electric shock outcomes for shock currents passing along different routes through the human body have been suggested. These factors may be of some use when analysing and estimating the risk of electric accidents in the special conditions present in mine excavations.

2. Effect of shock current passing via different paths

Of all the possible effects of an electric current passing through the human body, there are three basic ones, which should be mentioned:

a) the effect on the cardio-vascular system,

b) the effect on the nervous system and internal tissues,

c) the thermal effect.

The intensity of each of the above depends mainly on the path of the current. The most widely known details are those presented in report No 479-1 of International Electrotechnical Commission (Skutki... 1999). This is also regarded as comprising the most reliable criteria. They refer to the case of an a.c. current passage between left hand and both feet and for d.c., a convention with a direction from feet to left hand has been assumed (upward current).

These routes may be regarded as reference routes. Other current paths through the body may be experienced whilst working in an underground mine. This danger is mainly due to the special environmental conditions encountered at mining excavations. Examples are:

- lack of space at some excavations,
- large quantities of electric equipment as well as mining machinery and other electrically-powered appliances in the excavations,
- rocks and well-earthed metallic structures which are within easy reach,
- heavy covers and elements of the fire- proof housings of electric equipment, which are affixed by special locks or bolts,
- the need for certain specialist and sometimes precision jobs to be carried out in the vicinity of electric housings with difficult access in unfavourable ergonomic conditions,

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* The risk of direct contact also applies to persons who are not directly involved with electrically powered machinery at excavations but who may come into contact with relatively low-hanging (overhead contact system).

- protruding and sharp elements of housings and working electric equipment,
- the wearing of incomplete, wet or damaged working clothing.

Operators of electric equipment as well as other persons who have accidental contact with electric equipment are sometimes obliged to perform tasks in positions when unexpected contact with electric equipment is likely to happen. This allows it to be assumed that in electrical shock accidents the current may pass between any two, accidentally associated points of the body.

The following, most typical electrical contact points of the human body with electric circuits

have been identified: *G* — head, *Dl* — left foot, *Kp* — chest, *Sl* — left foot, *DD* — both hands, *SS* — both feet, *Sp* — right foot, *P* — back, *Dp* — right hand. When analysing risk, there is a need to estimate the effects of shock currents passing along paths between these points.

With regard to the effect of an electric current on the cardio-vascular system, the IEC report (Skutki... 1999) presents a method for the calculation of threshold currents which are responsible for ventricular fibrillation for the left hand — foot route, and for current values passing along other paths, according to the formula:

$$I_{r(A-B)} \cdot F_{(A-B)} = I_{r(Dl-SS)} \tag{1}$$

where:

$I_{r(A-B)}$	—	shock current passing along any path (from point *A* to point *B*),
$I_{r(Dl-SS)}$	—	shock current passing from the left hand to both feet,
$F_{(A-B)}$	—	heart current factor, allowing for propagation of a shock current, within the body and effect of the component of the current which is passing near the heart.

Heart current factors determined in (Skutki... 1999) have been compiled in the dark fields of Table 1. The conclusion that can be drawn from Table 1 is that heart-current factors are only named for about 35% of real paths routes. For other cases (shown by light fields), heart-factor values have been put forward on the basis of the following rules:

1. Heart fibrillation can be most easily caused by the passage of a current from chest to left hand (*Kp–Dl*): the heart-current coefficient then being $F_{(Kp-Dl)} = 1.5$. In the case of a current passing from the chest to both hands (*Kp–DD*) the same path is taken by the current and the effect on vascular system is equivalent.

2. The effect of a current passing from the chest to both limbs is equivalent to its effect while along the path from left hand to feet.

3. The effect of a current flow from the chest to back (*Kp–P*) is equivalent to its effect while along the path from the chest to right hand (*Kp–Dp*).

4. The effect of a current passing along both arms is equivalent to its effect while along the left hand (a more dangerous situation).

5. The effect of a current passing from back to feet is equivalent to the effect of its passage from the right hand to feet.

TABLE I

Heartcurrent factor $F_{a.c.}$ at alternating current shocks of 50 Hz frequency and direct current ($F_{d.c.}$, values in brackets)

TABLICA I

Wskaźnik prądu serca $F_{a.c.}$ przy rażeniach prądem przemiennym o częstotliwości 50 Hz i stałym ($F_{d.c.}$, wartości w nawiasach)

B/A	*G+*	*Dl+*	*Kp+*	*Sl+*	*DD+*	*SS+*	*Sp+*	*P+*	*Dp+*
G	0	1.5 (1.5)	1.5 (1.5)	0.8 (0.8)	1.5 (1.5)	0.8 (0.8)	0.8 (0.8)	0.8 (0.8)	1.3 (1.3)
Dl	1.5 (1.5)	0	1.5 (1.5)	1 (1)	0	1 (1)	1 (1)	0.7 (0.7)	0.4 (0.25)
Kp	1.5 (1.5)	1.5 (1.5)	0	1 (1)	1.5 (1.5)	1 (1)	1 (1)	1.3 (1.3)	1.3 (1.3)
Sl	0.8 (0.4)	1 (0.5)	1 (0.5)	0	1 (0.5)	0	0	0.8 (0.4)	0.8 (0.4)
DD	1.5 (1.5)	0	1.5 (1.5)	1 (1)	0	1 (1)	1 (1)	0.7 (0.7)	0 (0)
SS	0.8 (0.4)	1 (0.5)	1 (0.5)	0	1 (0.5)	0	0	0.8 (0.4)	0.8 (0.4)
Sp	0.8 (0.4)	1 (0.5)	1 (0.5)	0	1 (0.5)	0	0	0.8 (0.4)	0.8 (0.4)
P	0.8 (0.8)	0.7 (0.7)	1.3 (1.3)	0.8 (0.8)	0.7 (0.7)	0.8 (0.8)	0.8 (0.8)	0	0.3 (0.3)
Dp	1.3 (1.3)	0.4 (0.25)	1.3 (1.3)	0.8 (0.8)	0	0.8 (0.8)	0.8 (0.8)	0.3 (0.3)	0

Remarks: acc.: IEC 479 . relative (standard) path

6. The effect of a current passing from head to back and feet is equivalent to its effect while passing from back to feet.

7. The effect of a current passing from head to chest and arms is equivalent to the effect of its passage from chest to feet.

8. The effect of a downward (going down) d.c. current is equivalent to approximately half the effect of the upward (going up) current. This can be expressed by a formula:

$$I_r^{\downarrow} \cdot 0.5 = I_r^{\uparrow} \tag{2}$$

whereas differentiation between the upward and downward current refers only to the routes which involve the chest, trunk and feet.

9. D.C current passing across (*Dl–Dp*) may, as a rule cause ventricular fibrillation only at higher voltages (Markiewicz 1999; Skutki... 1999); its value being assumed to be double that of the downward current, i.e. four times higher than an upward current, according to the formula:

$$I_r^{\leftrightarrow} \cdot 0.25 = I_r^{\downarrow} \cdot 0.5 = I_r^{\uparrow} \tag{3}$$

The nature of the destructive effects of an electric current on the nervous system is hitherto imperfectly understood. This is shown among other facts, by the lack of the explicit establishment of criterion values. Simultaneously, results of examinations have confirmed thespecial role of the nervous system in the propagation of current as well as the possibility of neurone destruction by current flow. The effects of shocks on the nervous system may lead to fatal outcomes caused by disturbances of bio-automatic systems and the autonomous processes of body control. Ventricular fibrillation (if this occurs at all) may be then regarded as a secondary phenomenon, which has been initiated by the shock to the nervous system (Manoilov 1991). Lack of any quantitative information makes it difficult to define explicitly the influence of the current path on the effect on the nervous system. One can only assume hypothetically, that the results of nervous-system damage will depend on the length and route of the current path, attention being drawn to areas where there are organs of special importance (e.g. the head, the chest). The extent of the path, which depends among other factors on the distance between the points of inflow and outflow of the shock current is also important while taking into consideration the effect of an electric current on internal tissues. The unit which best describes bodily sensitivity to the effect of an electric current passing through the body is the electric field intensity (Manoilov 1991).

Based on the integral form of Ohm's law in the flow field (Goworkow 1962):

$$\int_A^B \overline{E}_{\text{wcwn}}\, dl \approx I_r \int_A^B \frac{dl}{\gamma \cdot s} = \Delta U_{A-B} \tag{4}$$

where

$\overline{E}_{\text{wewn}}$ — intensity of internal electric field along shock path from point A to point B,
I_r — shock current,
γ, s — conductivity and cross section of the tissue through which the current is passing

it can be assumed that drop of voltage between points A and B, ΔU_{A-B} corresponds to the extent of the current path between these points.

The thermal effect of the current results in the dissipation of power in an electric current field (along the shock path) in the body, which should be regarded as a complex, non-homogeneous conductor. The spatial density of power my be derived using a differential form of Joule's law (Goworkow 1962):

$$\lim_{\Delta V \to 0} \frac{\Delta P}{\Delta V} = \frac{J_r^2}{\gamma_c} \tag{5}$$

where:

J_r — current density,

γ_c — body conductivity.

Integrating the formula (5) within the limits of body's total volume, the thermal power released in the body can be assumed:

$$P = \int_V \frac{J_c^2}{\gamma_c} dV \tag{6}$$

Due to non-homogeneity and the body's changing cross section along the current path, it is essential to make certain simplifying assumptions which allow the thermal effects in the body to be defined approximately. The current path can be divided into segments of approximately constant cross section s_i. It can be noted for these sections:

$$dV_i = s_i \cdot dl \qquad \text{and} \qquad J_{ri} = \frac{I_r}{s_i} \tag{7}$$

Having substituted (7) for (6), Joule's law in integral form can be obtained. It describes the thermal power released at segment i of the shock route:

$$P_i = I_r^2 \cdot \int_{A_i}^{B_i} \frac{dl}{\gamma_{ci} \cdot s_i} \tag{8}$$

where:

A_i, B_i — beginning and end of segment i of the shock route, where a constant cross section can be assumed.

Total power released by the current passing from point A to point B will be the total of power dissipated at particular segments:

$$P_{A-B} = I_r^2 \cdot \sum_A^B \int_{A_i}^{B_i} \frac{dl}{\gamma_{ci} \cdot s_i} \tag{9}$$

Definite integrals in formulae (8) and (9) represent the resistances of particular body segments through via which the current passes.

Current routes can be represented by the resistances of particular segments. According to IEC guidelines (Skutki... 1999), the simplest electric scheme of the human body can be shown as in Fig. 1a. It is used for the estimation of approximate current values passing along different routes and on the assumption that the limbs' resistances are approximately equal ($R_r \approx R_n$). However, this scheme does not reflect the total effects of

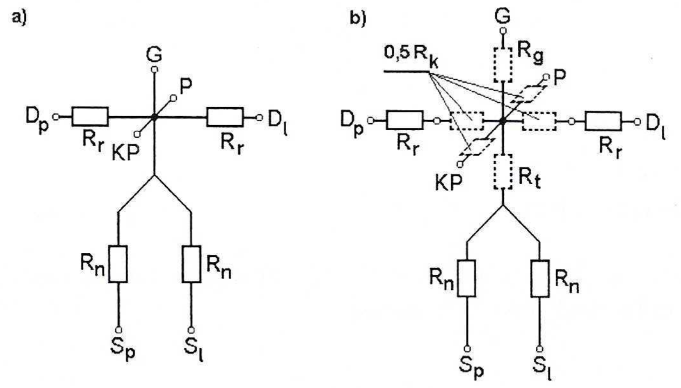

Fig. 1. Simplified substitute schemes of man's body applied for estimation of substitute resistance and results of shock current passing along different paths

Rys. 1. Uproszczone schematy zastępcze ciała człowieka stosowane do określania rezystancji zastępczej i skutków prądu rażeniowego płynącego różnymi drogami

a current, and especially the effects on nervous system and internal tissues. For example, in the schematic diagram shown in Fig. 1a no element (resistance) is attributed to effects of current passage via head, chest or trunk.

Taking into consideration the fact that the extent of a current route can be measured by the drop of voltage and that the most important organs of vascular system and nervous system are located inside the head, chest and trunk, a schematic diagram of human body can be drawn in the form shown in Fig. 1b. Conventionally, the resistances of substitute elements for the head (R_g), the chest (R_k) and thetrunk (R_t) can be initially assumed as being approximately equal and corresponding to the limbs' resistances:

$$R_r \approx R_n \approx R_g \approx R_k \approx R_t \approx R \tag{10}$$

The substitute resistance of the chest has been divided into halves in two planes perpendicular to each other, so that the schematic diagram could also reflect the effect of a current passing via the chest to the back and shoulders.

3. Conventional factors of alternating and direct current equivalence results for different paths

Regarding shock path from left hand to both feet as a reference (standard) path, the extent of shock for different shock current routes but for the same value of contact voltage can be conventionally estimated by introducing substitute factors of equivalence for particular effects, basing on the heart-current factor (Skutki... 1999).

A factor which describes the equivalence of the current effect on the cardio-vascular system for the same value of contact voltage can be obtained from the equation (Gawor 2000):

$$F_{F(A-B)} = F_{(A-B)} \cdot \frac{R_{z(A-B)}}{R_{z(Dl-SS)}} \tag{11}$$

where:

$F_{F(A-B)}$ — heart-current factor,

$R_{z(A-B)}$, and $R_{z(Dl-SS)}$ — body resistance between any two points $A - B$ and from the left hand to both feet.

Factor which describes effect of a current on the nervous system and internal tissues, depending on the extent of the shock path can be defined by the following expression where equation (4) has been taken into consideration:

$$F_{L(A-B)} = \frac{\sum_{Dl}^{SS} I_{i-j} \cdot R_{i-j}}{\sum_{A}^{B} I_{a-b} \cdot R_{a-b}} \tag{12}$$

where *i, j* and *a, b* mark the beginnings and ends of particular elements of the schematic diagram (Fig. 1) between points *Dl* and *SS* as well as *A* and *B* respectively. For the same value of contact voltage causing shock along different routes, the formula (12) takes the form:

$$F_{L(A-B)} = \frac{R_{z(A-B)} \sum_{Dl}^{SS} k_{i-j} \cdot R_{i-j}}{R_{z(Dl-SS)} \sum_{A}^{B} k_{a-b} \cdot R_{a-b}} \tag{13}$$

where factors k_{i-j} and k_{a-b} represent proportion between current passing via certain elements of the schematic diagram to the current which is entering the body:

$$k_{a-b} = \frac{I_{a-b}}{I_{A-B}} \quad \text{and} \quad k_{i-j} = \frac{I_{i-j}}{I_{Dl-SS}} \tag{14}$$

This factor allows for both the area of the body the shock current is passing through, as well as value of this current in particular elements of the schematic diagram.

The thermal effect factor of the current can be defined as the proportion between thermal power released by the current on the standard path (*Dl–SS*) and the power released on the current path defined by any two points *A–B*:

$$F_{Q(A-B)} = \frac{I_{Dl-SS}^2 \cdot R_{z(Dl-SS)}}{I_{A-B}^2 \cdot R_{z(A-B)}} \tag{15}$$

For the same value of contact voltage which results in a shock along different paths, formula (15) takes the form:

$$F_{Q(A-B)} = \frac{R_{z(A-B)}}{R_{z(Dl-SS)}} \tag{16}$$

The total effect of all three kinds of current effect along different paths can be estimated by summing up all three component factors. By introducing the notion of a resultant shock severity (or seriousness) factor, this can be expressed by a formula:

$$F_{w(A-B)} = w_F \cdot F_{F(A-B)} + w_L \cdot F_{L(A-B)} + w_Q \cdot F_{Q(A-B)} \tag{17}$$

where w_F , w_L and w_Q are weighting factors showing which effect is prevalent at the occurrence of bodily phenomena which result in a direct danger to health. Due to the lack of direct information, the share of the decisive factor is initially suggested to be assumed to be double its nominal value. Consequently, according to the opinion which makes the electric current effect on the cardio-vascular system basically responsible for heart fibrillation as expressed, among others, in IEC 479 report (Skutki... 1999), increased weighting should be attributed to the fibrillation factor F_F. This may be expressed by a formula:

$$F^{F}_{w(A-B)} = 2 \cdot F_{F(A-B)} + F_{L(A-B)} + F_{Q(A-B)} \tag{18}$$

Being in favour of the opinion of the vital importance of the effect on nervous system, which leads to neurone damage and degradation of bio-automatic systems as well as autonomic body control processes (these have been shown in Manoilov (1991)working hypothesis), factor F_L should be given increased weighting:

$$F^{L}_{w(A-B)} = F_{F(A-B)} + 2 \cdot F_{L(A-B)} + F_{Q(A-B)} \tag{19}$$

Assuming a simultaneous effect on both the cardio-vascular system and the nervous system (thermal effect being caused by internal current passage only, i.e. without burns caused by electric arcing, can be regarded as less important in comparison to the others), the resultant shock degree factor will be expressed by a formula:

$$F^{FL}_{w(A-B)} = 2 \cdot F_{F(A-B)} + 2 \cdot F_{L(A-B)} + F_{Q(A-B)} \tag{20}$$

Values of particular shock degree factors for selected shock degree passage paths, calculated according to formulae (18), (19) and (20), and taking into consideration theoretical resistances which result from the schematic diagram as per Fig. 1b (Gawor 2000), have been compiled in Tables 2 and 3.

In order to compare the results of shock along different paths, relative values of resultant factors have been additionally shown in Tables 4 and 5. These relate to the path left hand-both feet (*Dl–SS*) and have been calculated according to the formula:

$$\underline{F}^{i}_{w(A-B)} + \frac{F^{i}_{w(A-B)}}{F^{i}_{w(Dl-SS)}} \tag{21}$$

Additionally, values of factor $F_{w(A-B)}$ and $\underline{F}_{w(A-B)}$ calculated on the assumption that weighting factors in formula (17) are unitary are shown in Tables 2 to 5.

TABLE 2

Resultant factors of alternating current (a.c.) shock degree, passing along selected paths *A–B*

TABLICA 2

Wypadkowe wskaźniki stopnia porażenia prądem przemiennym (a.c.) płynącym wzdłuż wybranych dróg *A–B*

A–B	*Dl–SS*	*Dp–SS*	*Dp–Dl*	*Dp–Kp*	*Dl–Kp*	*DD–SS*	*DD–Kp*	*G–Kp*
$F_{w(A-B)}$	3.00	2.80	2.57	2.71	2.85	2.25	1.78	2.42
$F^{F}_{w(A-B)}$	4.00	3.60	2.97	3.58	3.85	3.00	2.41	3.17
$F^{L}_{w(A-B)}$	4.00	3.80	3.74	3.88	4.02	3.00	2.51	3.59
$F^{FL}_{w(A-B)}$	5.00	4.60	4.14	4.75	5.02	3.75	3.14	4.34

TABLE 3

Resultant factors of direct current (d.c.) shock degree, passing along selected paths *A–B*

TABLICA 3

Wypadkowe wskaźniki stopnia porażenia prądem stałym (d.c.) płynącym wzdłuż wybranych dróg *A–B*

A–B	*SS–Dl* (*Dl–SS*)	*SS–Dp* (*Dp–SS*)	*Dp–Dl* (*Dl–Dp*)	*Dp–Kp* (*Kp–Dp*)	*Dl–Kp* (*Kp–Dl*)	*SS–DD* (*DD–SS*)	*DD–Kp* (*Kp–DD*)	*G–Kp* (*Kp–G*)
$F_{w(A-B)}$	3.00 (2.50)	2.80 (2.40)	2.42 (2.42)	2.71 (2.71)	2.85 (2.85)	2.25 (1.88)	1.78 (1.78)	2.42 (2.42)
$F^{F}_{w(A-B)}$	4.00 (3.00)	3.60 (2.80)	2.67 (2.67)	3.58 (3.58)	3.85 (3.85)	3.00 (2.25)	2.41 (2.41)	3.17 (3.17)
$F^{L}_{w(A-B)}$	4.00 (3.50)	3.80 (3.40)	3.59 (3.59)	3.88 (3.88)	4.02 (4.02)	3.00 (2.63)	2.51 (2.51)	3.59 (3.59)
$F^{FL}_{w(A-B)}$	5.00 (4.00)	4.60 (3.80)	3.84 (3.84)	4.75 (4.75)	5.02 (5.02)	3.75 (3.00)	3.14 (3.14)	4.34 (4.34)

TABLE 4

Relative values of resultant alternating current (a.c.) shock degree current, passing along selected paths *A–B*

TABLICA 4

Względne wartości wypadkowych wskaźników stopnia porażenia prądem przemiennym (a.c.) płynącym wzdłuż wybranych dróg *A–B*

A–B	*Dp–SS*	*Dp–Sl,p*	*Dp–Dl*	*Dp–Kp*	*Dl–Kp*	*Dl–Sl,p*	*DD–SS*	*DD–Kp*	*G–Kp*
$\underline{F}_{w(A-B)}$	0.933	1.093	0.857	0.903	0.950	1.170	0.750	0.593	0.807
$\underline{F}^{F}_{w(A-B)}$	0.900	1.053	0.743	0.895	0.963	1.170	0.750	0.603	0.793
$\underline{F}^{L}_{w(A-B)}$	0.950	1.113	0.935	0.970	1.005	1.170	0.750	0.628	0.898
$\underline{F}^{FL}_{w(A-B)}$	0.920	1.076	0.828	0.950	1.004	1.170	0.750	0.628	0.868

TABLE 5

Relative values of resultant direct current (d.c.) shock degree current, passing along selected paths *A–B*

TABLICA 5

Względne wartości wypadkowych wskaźników stopnia porażenia prądem stałym (d.c.) płynącym wzdłuż wybranych dróg *A–B*

A–B	*SS–Dp* (*Dp–SS*)	*Dp–Sl,p.* (*Sl,p.–Dp*)	*Dp–Dl* (*Dl–Dp*)	*Dp–Kp* (*Kp–Dp*)	*Dl–Kp* (*Kp–Dl*)	*Dl–Sl,p.* (*Sl,p–Dl*)	*SS–DD* (*DD–SS*)	*DD–Kp* (*Kp–DD*)	*G–Kp* (*Kp–G*)
$\underline{F}_{w(A-B)}$	0.933 (0.960)	0.937 (1.093)	0.807 (0.968)	0.903 (1.084)	0.950 (1.140)	0.977 (1.170)	0.750 (0.752)	0.593 (0.712)	0.807 (0.968)
$\underline{F}^{F}_{w(A-B)}$	0.900 (0.933)	0.820 (1.053)	0.668 (0.890)	0.895 (1.193)	0.963 (1.283)	0.878 (1.170)	0.750 (0.750)	0.603 (0.803)	0.793 (1.057)
$\underline{F}^{L}_{w(A-B)}$	0.950 (0.971)	0.995 (1.113)	0.898 (1.026)	0.970 (1.109)	1.005 (1.149)	1.025 (1.170)	0.750 (0.751)	0.628 (0.717)	0.898 (1.026)
$\underline{F}^{FL}_{w(A-B)}$	0.920 (0.950)	0.890 (1.076)	0.768 (0.960)	0.950 (1.188)	1.000 (1.255)	0.936 (1.170)	0.750 (0.750)	0.628 (0.785)	0.868 (1.085)

4. Conclusion

Rules for estimating the resultant shock severity factors for an electric current passing through different bodily paths are based on statements which are known from the literature and result from fairly or less numerous surveys on people and animals as well as on electrical accident analysis. The suggested factors are of hypothetical nature and may be used for conventional estimation of shock effects only. Their values draw attention to important phenomena which may accompany an electric current shock which passes along different paths. Due to the character of the subject and the method of investigation, there is no need for experimental verification of its correctness. It is, however, advisable to elaborate such factors in the context of the need quantify risk estimation for a safety management system.

Four kinds of factors (F_w, F_w^F, F_w^L, F_w^{FL}) make possible the particular consideration of different current effects on the body. The factors' relative values, as compiled in tables 4 and 5 point at two characteristic features:

- values of particular factors corresponding to certain shock routes are differ little; this being an argument to confirm the validity of a suggested global consideration of all possible shock results;
- total values of factors (i.e. most dangerous shock results) refer to the passage of shock current from the left hand to one of the feet as well as from the left or right hand to the chest.

Electric current shock severity is an element of the risk in electric accidents which occur in underground mines and should be considered in the context of the ergonomic factors created by the special environmental conditions at the place of work.

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