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Influence of movements in tectonic fault on stress-strain state of the pipeline ČHE Kozjak

Vpliv premikov v prelomni coni na napetostno deformacijsko stanje cevovoda ČHE Kozjak

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Abstract: In the frame of pumping hydroelectric station Kozjak the construction of pipeline's tunnel in length of 2400 m that overcomes 710 m of see level difference between machine house and reservoir hydraulic drop is foreseen. The pipeline layout is mostly in layers of compact rock, and it overcome eleven tectonic faults. Material in these faults is remolded and weathered due to water presence, and according to the preliminary estimation the width of tectonic faults is between 25 m and 80 m. The analysis considers deformations and stresses in pumping pipeline due to movements in tectonic fault. To estimate this stress-strain response mathematical model in form of differential equation was made.

The variables in analysis were relative movement in tectonic fault, width of tectonic fault, area of pipeline cross-section, pipeline strength, compact rock strength and remolded rock strength. Inner forces or stresses and strains in pipeline cross-section were determined through analysis. It was found out that the width of tectonic fault essentially influence their distribution along tectonic fault width. The analytical solutions were compared with solution obtained according to the finite element method.

Izvleček: V sklopu graditve črpalne hidroelektrarne Kozjak je predvidena gradnja tlačnega cevovoda dolžine 2400 m, ki bo premagoval skupni padec 710 m. Trasa cevovoda poteka pretežno v slojih kom-

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paktnih kamnin. Problem je, da vzdolžno prečka enajst prelomnih con. Na teh mestih je hribina razdrobljena in zaradi dotokov vode preperela. Po prognoznih podatkih je širina takih con med 25 m in 80 m. Analiza obravnava deformacije in napetosti tlačnega cevovoda zaradi premikov v prelomni coni. Za določitev napetostno deformacijskega odziva zaradi pomikov v prelomni coni je bil izdelan matematični model v obliki diferencialnih enačb.

V analizi so bile spremenljivke velikost relativnega pomika v prelomni coni: širina prelomne cone, prerez cevovoda, trdnost cevovoda, trdnost kompaktne hribine in trdnost pregnetene hribine. Določale pa so se notranje statične količine oz. napetosti in deformacije v prerezu cevovoda. Ugotovljeno je bilo, da je bistvenega pomena za njihovo razporeditev širina prelomne cone. Analitične rešitve so bile primerjane z rešitvami, dobljenimi po metodi končnih elementov.

Key words: tectonic fault, tunnel, tunnel deformation, rock stiffness
Ključne besede: prelomna cona, predor, deformacija predora, togost kamnine

INTRODUCTION

The construction of pipeline’s tunnel of pumping hydroelectric station Kozjak is foreseen. It is composed of three main parts: engine house, accumulation lake, and the pipeline that connects engine house and reservoir. The engine house is located near river Drava, reservoir is on the 700 m higher plateau of Kozjak, and the pipeline is few ten meters under its eastern slope.

The geological characteristics were preliminary investigated in 1979 and 1980. The further activities of the project were stopped, until it was anew activated in year 2004. The project is in the outline scheme phase.

The paper considers only the problem of tunnel’s deformations and stresses due to the movements in tectonic faults. The main questions that arise are:

- deformation of the tunnel’s structure,
- distribution of normal and shear stresses in the tunnel’s cross-section,
- bending moments and shear forces in the tunnel’s cross-section,
- influence of the movement in tectonic fault, the tectonic fault’s width, and the ratio of stiffness in compact rock and tectonic fault.

In order to answer the questions that arise, mathematical model of the problem was made. The model encounters morphological and geomechanical properties of the ground, geometry of the planned pipeline, and technological conditions of the pipeline erection. Model is given in the form of differential equations together with assumed boundary conditions that follows geometry and technology of the construction. The solutions of the equations are functions of deflection, slope, bending moment, shear force, and resistance intensity.

The analytical solutions were compared with solutions obtained according to finite element method (FEM) and using program code Plaxis 3D Tunnel.

GEOLOGY

The geological characteristics given in geological reports were determined using field geological reconnaissance, photo-geological analyses, and hydro-geological, geophysical and sounding investigations. The results of investigations are given in geological-geotechnical reports [1], [2] that give: geomorphologic description, geologic structure, hydrogeological conditions and tectonics. In 2004 the additional investigations and supplement geotechnical report was done [3] that present review of established geological characteristics of preliminary reports, geotechnical analyses and proposal of supplementary investigations for the realization of planned project. The longitudinal section through pipeline with geology is on Figure 1.

Geomorphologic description

The pipeline's tunnel is designed deep in the slope of eastern Kozjak between Drava River and Kolar's peak. The agitated formed terrain is characteristic, that is the result of geological structure, tectonic, precipitation conditions and the formation history of the ground. The valleys and ravines are bounded mostly on older and bigger tectonic faults where the erosion is more intensive due to crumbled rocks. The crests are connected with very steep slopes appears where compact and more subsistence rocks. On the peaks of the ascents where the activity of surface waters is less distinctive thicker decaying cover and distinctive dome-shaped peaks rise.

Geological structure

The major part of the investigated region belongs to the metamorphic rock complex characteristic for the whole region of central Alps. The metamorphic rocks originated mainly at regional metamorphosis bounded on extensive orogenic zones.

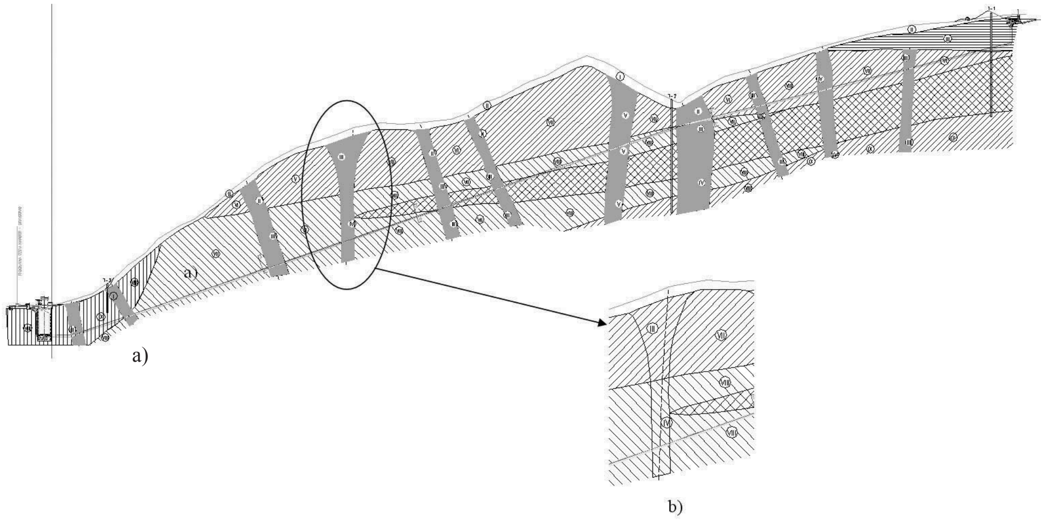

Figure 1. Geology with pipeline: a) longitudinal cross-section, b) enlargement of the tectonic fault

The most widened rocks of the investigated region comprise blestnik and gneisses that are irregular interchange in thinner and thicker layers. On the slope peaks of the investigated region presents those rocks basis of diaphtorite and diaphtorite schists. The described rocks appear on the surface on the steep slopes in direction of pipeline line, they can be tracked also down to the foothill of the slope.

The upper part of the upper half of the tunnel alignment is mainly composed of blestnik and the lower portion mainly of gneiss. Both series are intercalated by amphibolites and biotite-epidote schists. The occurrence of amphibolites is rather rare at higher elevations. The amphibolites may grade into the schists in places.

The next series in flow direction is composed of marble, calcite bearing blestnik, dolomite, and calcitic schists in irregular sequences. The calcitic schist forms the transition between marble, carbonaceous schist and biotite-muscovite, blestnik or gneiss, respectively. All layers are dipping steeply to vertical, i.e. between 60° and 90° towards south or north due to intense folding. Further downstream the inclination flattens to 30° to 60° with decreasing intensity of folding.

The slopes are mainly covered by in-situ weathered materials from the underlying bedrock. The overburden is composed of sand and angular fragments of rock in different degrees of weathering. The thickness depends on the steepness of the slope as follows: steep slope (0.5–1.5 m), moderate slope (1.0–2.0 m), and flat slope (2.0–5.0 m).

Tectonic

The project area is composed of Cambrian sediments, which have undergone orogenic deformations and metamorphosis. It is deemed that the metamorphosis occurred in several sequences and the final stage resulted in a retrograde metamorphosis, in which the minerals were adjusted to lower temperatures and pressures. Lateral pressures have lead to intense folding and in a second phase to foliation. Dilatation movements resulted in a more or less regular pattern of fractures forming blocks of different size.

The tectonic systems of wide considered region were defined on basis of field recognition, photo-geological analyses and geophysical investigations. Three tectonic systems were stated, namely in directions SW-NE, W-E and N-S to NW-SE.

At tectonic zones mainly vertical movements appear. The width of cracked zones is 5–80 m, water inflows are possible in this places 0.5–5 L/s. The widest tectonic zones, the highest water inflows and higher seismic activities at tectonic zones of the systems N-S to NW-SE.

Hydro-geological conditions

The hydro-geological situation was investigated by surface mapping and drilling works (inflow and rising head test, and water level measurements in boreholes).

In principle two different aquifers were encountered. The first type is confined to the open joints in the bedrock, and the second type to the pores of the alluvial gravel. The area between the valley and the upper reservoir is governed by the first type of aquifer. The permeability depends on the frequency and openness of the joints. The permeability was tested by water pressure tests. The medium cracked rocks have the coefficients of permeability between 5×10^{-6} and 1×10^{-9} m/s. In tectonic zones with strongly crumbled rock material the coefficients of permeability are essentially higher. The measurements in rocks with equal RQD showed that the values vary between 5×10^{-4} and 5×10^{-7} m/s.

In the region of the pipeline's line no continuous ground water level is presented. The filtrated water appears in cracks and tectonic crumbled or weathered zones.

Engineering geological and geotechnical characteristics

Regards to the degree of rock crackness in the region of the pipeline are classified in ten categories. First five categories present weathered and strongly tectonic cracked rocks, that have $RQD < 30$ and $Q < 1$. In higher categories belongs partly cracked to compact rocks.

The line of the pipeline course mostly in rock layers of category VII to IX; however it crosses eleven tectonic faults of system N-S and NW-SE. On these places the rock is crumbled and due to the water inflow also decaying. According to the prognosis can be classified in categories I to V, the width of such zones is between 25 m and 80 m. The foreseen properties of the rock in the course of pipeline are given in Table 1.

PROJECT DATA

The inner diameter of the pipeline is 3.0 m, the wall is of reinforced concrete (RC), width of 50 cm. The pressure tunnel of length 2400 m overcomes total fall of 710 m. In up-

Table 1. Properties of rocks in pipeline region

properties	$RMR^{(1)}$	$Q^{(2)}$	category$^{(3)}$	$k^{(4)}$/	water flow$^{(5)}$
rock				(m/s)	(L/s)
cracked and weathered (17 %)	25–45	0.07–1.0	I–V	5×10^{-4}–5×10^{-7}	≥ 1, smaller water invasion
partially cracked to compact (83 %)	60–72	5–24	VI–X	5×10^{-6}–1×10^{-9}	wet, light to strong dropping

(1) Bieniawski

(2) Barton et al.

(3) Categorization regarding to degree of rock crack ness

(4) Coefficient of water permeability, filling test in boreholes T-1, T-2 and T-3

(5) Expected water flow regarding to degree of rock crack ness

per part firstly drops vertical 40 m, then course in slope about 31 %. In front of the powerhouse shaft course pipeline in length of 60 m horizontal, and then split into two legs, that leads in underground shaft of the powerhouse.

The pipeline crosses eleven tectonic zones. The rocks in tectonic zones are remolded, their strength is instantly lower than in compact rocks.

The geotechnical conditions of pumping tunnel construction are given in geological-geotechnical documentation. [3], [4] The technology is not defined yet.

The pressure tunnel will be loaded with constant and repeated loading. The constant load present outer soil pressure and pipeline own weight. The constant load is equal:

$\sigma_{\mathrm{v}} = 0.8–1$ MPa
$\sigma_{\mathrm{h}} < \sigma_{\mathrm{v}}$

The stress in the structure and expected movements due to constant load are:

$\sigma_r = 0.8–1$ MPa (compression)
$\sigma_\varphi = 3.6–4.5$ MPa (compression)
$u_r \cong 0.2$ mm

The repeated load presents the change of the inner pressure:
$p = 0–7$ MPa
$p_{\max} = 11$ MPa

The stress in the structure and expected movements due to repeated load are:

$\sigma_r = 8–11$ MPa (compression)
$\sigma_\varphi = 25–39$ MPa (tension)
$u_r \cong 1–2$ mm

Due to the possible movements in tectonic tones the additional load can appear as relative movement of the ground at the contact in tectonic zone. The magnitude of the movement in analysis is supposed at $u_{\mathrm{rel}} = 1–10$ mm.

Mathematical model

The pipeline is axis-symmetrical with r, ϑ, x coordinates, where x-axis corresponds with the pipeline axis. The pipeline is erected in the ground, described in the space by x, y, z coordinates, where x-axis corresponds with the pipeline axis, while y-axis is vertical.

The geometrical and mechanical characteristics of the pipeline and surrounding rock are given in Table 2.

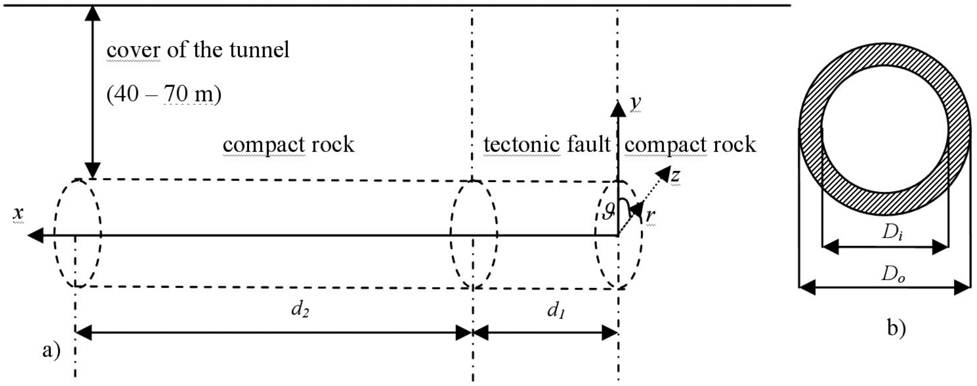

Figure 2. Mathematical model: a) longitudinal cross-section, b) pipeline cross-section.

Table 2. Geometrical and mechanical properties of pipeline and rock

d_1 = 25–80	m	width of tectonic fault in the pipeline axis
d_2 = 80–200	m	width of compact rock in the pipeline axis
D_i = 3.0	m	inner tube diameter
D_o = 4.0	m	outer tube diameter
$E = 30 \times 10^6$	kPa	elasticity modulus of the tube
I = 8.6	m^4	inertia moment of the tube
u_0 = 0–10	mm	movement in tectonic fault
E_1 = 0–1	GPa	elasticity modulus of tectonic fault
E_2 = 20–30	GPa	elasticity modulus of compact rock

The pipeline is subjected to the permanent stresses of the surrounding rock (0.3–2 MPa), repeated water pressure (7–10 MPa), and eventual movements in tectonic fault (few millimeters). The presented stress-strain analysis considers only eventual movements in tectonic fault.

k_1	stiffness of tectonic fault
k_2	stiffness of compact rock
EI	flexural stiffness of tunnel (pipeline)
$y(x)$	deflection line
$y'(x)$	slope line
$EIy''(x)$	bending moment line
$EIy'''(x)$	shearing force line
$q(x)$	resistance of rock in tectonic fault

The general differential equation for footing on elastic subsoil is given:

$$EI\frac{d^4y(x)}{dx^4}=q(x) \tag{1}$$

where the resistance of rock in tectonic fault can be expressed with function:

$$q(x)=k_1\cdot y(x) \tag{2}$$

then Eq. (1) gets the following form:

$$EI\frac{d^4y(x)}{dx^4}-k_1\cdot y(x)=0 \tag{3}$$

The general solution according to [5] is:

$$\begin{aligned} y(x)&=C_1\cdot e^{-x\cdot\sqrt[4]{\frac{-k_1}{EI}}x}+C_2\cdot e^{x\cdot\sqrt[4]{\frac{-k_1}{EI}}x}+\\ &+C_3\cdot e^{-x\cdot\sqrt[4]{\frac{(-1)^3\cdot k_1}{EI}}x}+C_4\cdot e^{x\cdot\sqrt[4]{\frac{(-1)^3\cdot k_1}{EI}}x} \end{aligned} \tag{4}$$

We can introduce the following assumptions:

- the pipeline is within elastic domain,
- the pipeline is subjected to the displacement at the contact between compact rock and rock in tectonic fault [$y(x=0)=u_0$],
- the stiffness of compact rock k_2 is very high comparing to the stiffness of rock in tectonic fault k_1 [$20\times k_1<k_2$],
- displacement on the other contact between compact rock and rock in tectonic fault is assumed to be equal zero [$y(x=d_1)=0$],
- rotations on both contacts between compact rock and rock in tectonic fault are assumed to be equal zero [$y'(x=0)=y'(x=d_1)=0$; $y''(x=d_1/2)=0$].

The function of rock's resistance in tectonic fault $q(x)$ has to be in accordance with deflection line $y(x)$, then we can approximate the rock's resistance line with adequate function, for example:

$$\begin{aligned} q(x)&=q_0\cdot\left(1+\cos\left(\pi\frac{x}{d_1}\right)\right)=\\ &=k_1\cdot y_0\cdot\left(1+\cos\left(\pi\frac{x}{d_1}\right)\right) \end{aligned} \tag{5}$$

where, $q_0=k_1\times y_0$ is resistance in the middle of the tectonic fault at $x=d_1/2$, and y_0 is about half of tectonic movement u_0. Then Eq. (3) gets the form:

$$EI\frac{d^4y(x)}{dx^4}=q_0\cdot\left(1+\cos\left(\pi\frac{x}{d_1}\right)\right) \tag{6}$$

this leads using above boundary conditions (given in assumptions) to the solution:

$$y(x) = u_0\left[2\left(\frac{x}{d_1}\right)^3 - 3\left(\frac{x}{d_1}\right)^2 + 1\right] + \frac{q \cdot d_1^4}{24 \cdot \pi^4 \cdot EI}\left[-24 + \pi^4 \cdot \left(\frac{x}{d_1}\right)^2 + 144 \cdot \left(\frac{x}{d_1}\right)^2 - 2 \cdot \pi^4 \cdot \left(\frac{x}{d_1}\right)^3 - 96 \cdot \left(\frac{x}{d_1}\right)^3 + \pi^4 \cdot \left(\frac{x}{d_1}\right)^4 + 24 \cdot \cos\left(\pi \cdot \frac{x}{d_1}\right)\right] \tag{7a}$$

$$y'(x) = \frac{u_0}{d_1}\left[6\left(\frac{x}{d_1}\right)^2 - 6\left(\frac{x}{d_1}\right)\right] + \frac{q \cdot d_1^3}{12 \cdot \pi^4 \cdot EI}\left[\pi^4 \cdot \left(\frac{x}{d_1}\right) + 144 \cdot \left(\frac{x}{d_1}\right) - 3 \cdot \pi^4 \cdot \left(\frac{x}{d_1}\right)^2 - 144 \cdot \left(\frac{x}{d_1}\right)^2 + 2 \cdot \pi^4 \cdot \left(\frac{x}{d_1}\right)^3 - 12 \cdot \pi \cdot \sin\left(\pi \cdot \frac{x}{d_1}\right)\right] \tag{7b}$$

$$M(x) = EI \cdot y''(x) = EI \cdot \frac{u_0}{d_1^2}\left[12\left(\frac{x}{d_1}\right) - 6\right] + \frac{q \cdot d_1^2}{12 \cdot \pi^4}\left[\pi^4 + 144 - 6 \cdot \pi^4 \cdot \left(\frac{x}{d_1}\right) - 288 \cdot \left(\frac{x}{d_1}\right) + 6 \cdot \pi^4 \cdot \left(\frac{x}{d_1}\right)^2 - 12 \cdot \pi^2 \cdot \cos\left(\pi \cdot \frac{x}{d_1}\right)\right] \tag{7c}$$

$$Q(x) = EI \cdot y'''(x) = 12 \cdot EI \cdot \frac{u_0}{d_1^3} + \frac{q \cdot d_1}{2 \cdot \pi^4}\left[-\pi^4 - 48 + 2 \cdot \pi^4 \cdot \left(\frac{x}{d_1}\right) + 2 \cdot \pi^3 \cdot \sin\left(\pi \cdot \frac{x}{d_1}\right)\right] \tag{7d}$$

Above solutions are given as functions of $q_0 = k_1 \times y_0$, that can be theoretically, in the case when k_1/k_2 approaches very small values, even zero. In the latter case the Eqs. (7) get the following form:

$$y(x) = u_0\left[2\left(\frac{x}{d_1}\right)^3 - 3\left(\frac{x}{d_1}\right)^2 + 1\right] \tag{8a}$$

$$y'(x) = \frac{u_0}{d_1}\left[6\left(\frac{x}{d_1}\right)^2 - 6\left(\frac{x}{d_1}\right)\right] \tag{8b}$$

$$M(x) = EI \cdot y''(x) = = EI \cdot \frac{u_0}{d_1^2}\left[12\left(\frac{x}{d_1}\right) - 6\right] \tag{8c}$$

$$Q(x) = EI \cdot y'''(x) = 12 \cdot EI \cdot \frac{u_0}{d_1^3} \tag{8d}$$

This is well known solution that can be obtained using mechanics theory of elastic liner structures.

It can be realized, that results are influenced by the following factors:

- cross-section of the tube
- strength of the tube
- strength of the compact rock
- strength of the rock in tectonic zone
- quantity of the relative movement in tectonic zone
- width of the tectonic zone

The cross-section and the strength of the pressure tunnel do not influence deformations and inner forces in the structure, but they are important for stress state in tunnel structure. Increasing cross-section and strength of the tunnel structure lead to inversely proportional lower stresses in the cross-section of the tunnel.

The strength of the compact rock and strength of the remolded rock do not influence the magnitude and distribution of the movement and rotation of the tunnel structure (Figure 3), but they influence on the magnitude and distribution of inner forces of the tunnel structure. The distribution of inner forces is influenced also by ratio between strength of compact and remolded rock (Figure 4).

The inner forces, respectively stresses and deformations (movements, rotations) linearly depend on magnitude or the relative movement in tectonic zone (Figures 3, 4).

The width of the tectonic zone is essential for the distribution of deformations and inner forces across tunnel cross-section. Lowering tectonic zone width leads to non linear increasing of inner forces. Figure 5 presents inner forces at the edge of the tectonic zone for movement in tectonic zone equal $u = 1$ mm.

The analysis of stress distribution across tunnel cross-section shows, that the supposed properties of the pressure tunnel and rock significantly increase inner forces when the with of the tectonic zone is lower than 30 m. The with above 30 m is problematic concerning magnitude of inner forces also at supposed higher movements in tectonic zone, therefore deviation of the results in this region are not important.

The analytical solutions were compared with solutions obtained according to the finite element method (FEM). The results of analyses are presented in Figure 7 and are comparable to the results of analytical solutions.

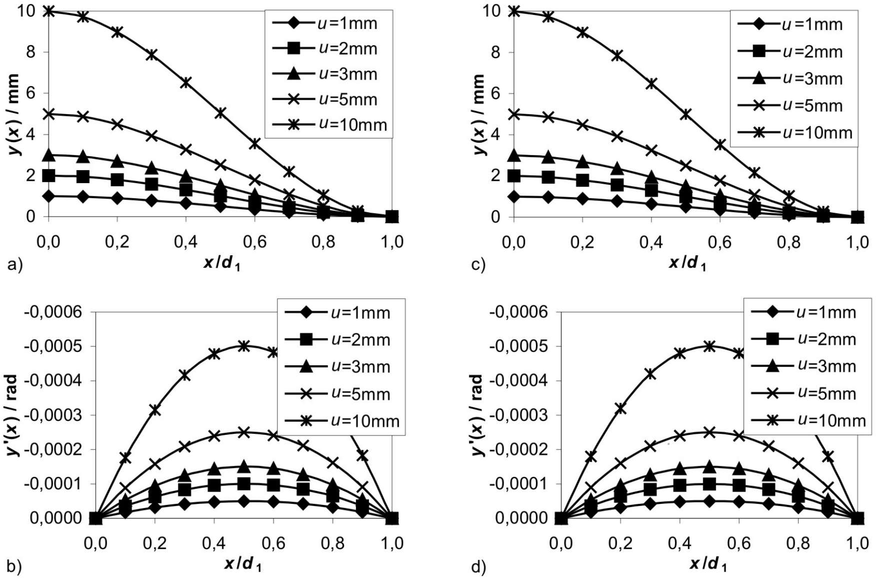

Figure 3. Results for different movements *u* in joint for d_1 = 30 m and k_1 = 10 MPa/m: a) movement, b) rotation; and for d_1 = 30 m and k_1 = 0: c) movement, d) rotation

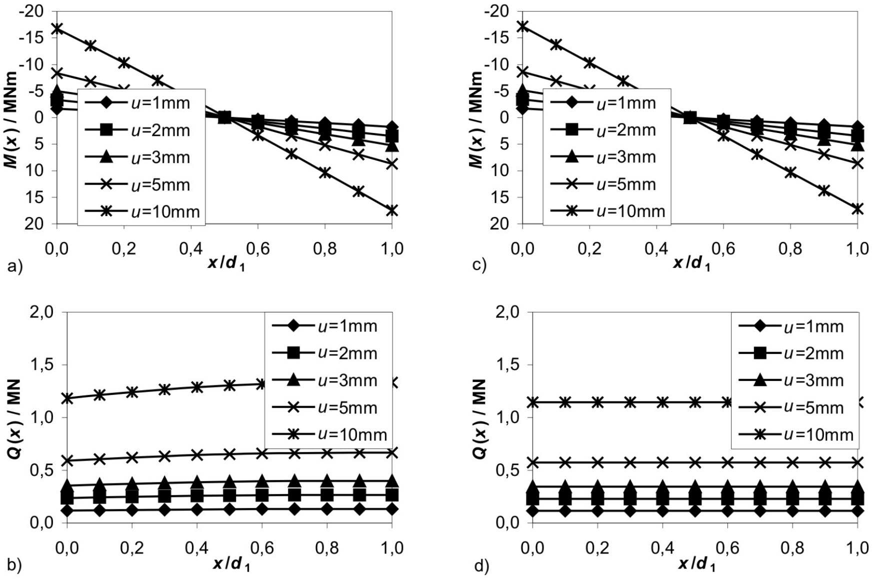

Figure 4. Results for different movements *u* in joint for d_1 = 30 m in k_1 = 10 MPa/m: a) bending moment; b) shear force; and for d_1 = 30 m in k_1 = 0: c) bending moment; d) shear force

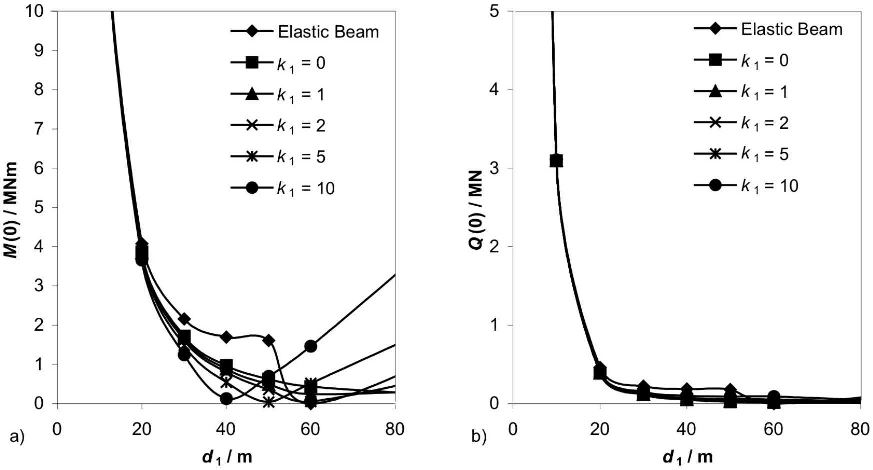

Figure 5. Inner forces as function of tectonic fault width: a) bending moment, b) shear force.

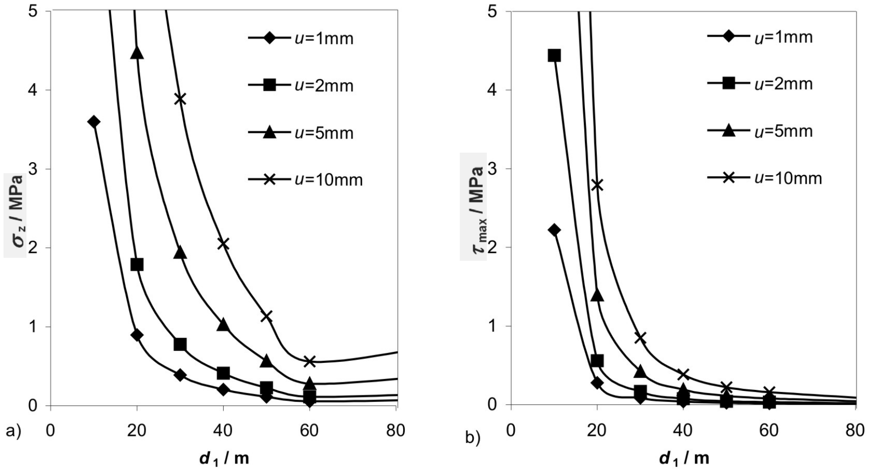

Figure 6. Stress for different movement *u* as function of tectonic fault width for d_1 = 1 MPa/m: a) normal stress, b) shear stress.

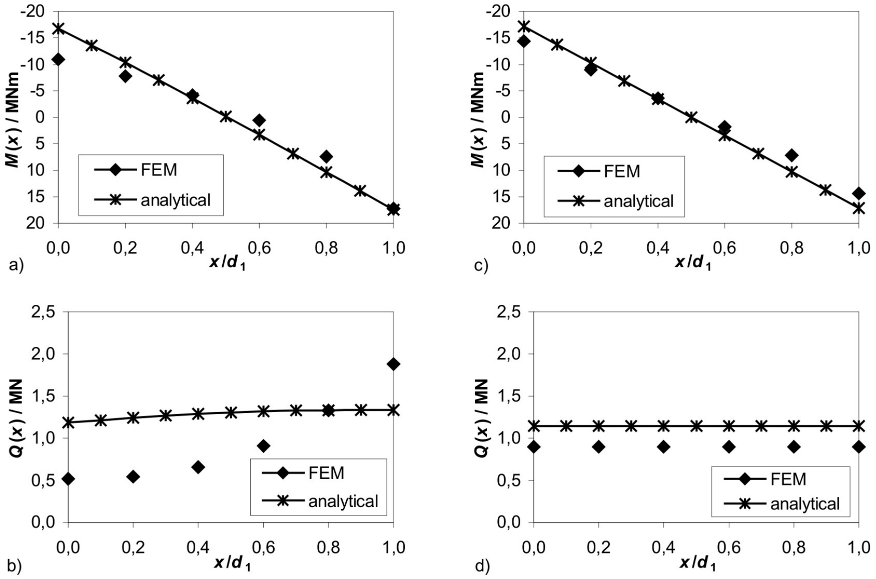

Figure 7. Results of analytical solutions and values obtained using FEM for movement u = 10 mm in joint for d_1 = 30 m in k_1 = 10 MPa/m: a) bending moment; b) shear force; and for d_1 = 30 m in k_1 = 0: c) bending moment; d) shear force.

CONCLUSIONS

To find the stress-strain response due to the movement in tectonic fault, the mathematical model was made in the form of differential equations. The general solution of the problem is given which is not in the closed form. Introducing assumed shape of the deflection line that is in accordance with the resistance line of the rock in tectonic fault, we obtain the simple solution in a closed form.

The solutions of the equations are functions of deflection, slope, bending moment, shear force, and resistance intensity.

The analysis shows, that the magnitude of the movement in tectonic fault, width of tectonic fault, cross-section and strength of the tunnel, and stiffness of tectonic fault and compact rock essentially influence the magnitude of the stresses and deformations of the tunnel structure.

The inner forces, respectively stresses and deformations linearly depend on the magnitude of the relative movement in tectonic cone.

The cross-section and the strength of the pressure tunnel do not influence magnitudes of the movement and rotation of the tunnel. Increasing cross-section and strength of the tunnel structure lead to inversely proportional lower stresses in the cross-section of the tunnel.

The strength of the compact rock and strength of the remolded rock do not influence the magnitude and distribution of the movement and rotation of the tunnel structure. However, they influence on the magnitude and distribution of inner forces of the tunnel structure. The distribution of inner forces is influenced also by ratio between strength of compact and remolded rock (Figure 4). The width of the tectonic zone is essential for the distribution of deformations and inner forces across tunnel cross-section. Lowering tectonic zone width leads to non linear increasing of inner forces.

The analysis of stress distribution across tunnel cross-section shows, that the supposed properties of the pressure tunnel and surrounding the critical width of the tectonic zone is between 20 m and 30 m. For width above 30 m the magnitudes of inner forces exceedingly fall also at supposed higher movements in tectonic zone.

The results of analytical solutions are comparable with results obtained according to FEM.

The advantage of the analytical solutions is in presentation of the results in form of function, while the calculation according to FEM gives the results for certain chosen geometrical and material data.

Acknowledgments

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