Tension cracking in injection anchorages

Les fissures dues à la traction dans les tirants injectés

G.O. Degil & W.G.K. Fleming – *UK*

ABSTRACT: The aim of this paper is to examine theoretically the behaviour of injection anchors having differing ultimate load shearing behaviour with regard to the crack-forming internal force. Two stages in the stress-strain state within an anchor are examined: firstly from the initial application of load when the anchor acts as a whole body until the first crack appears in the body of the fixed anchor length; secondly after cracks have formed normal to the longitudinal axis and their propogation along the fixed length. These cases are distinguished by levels of stiffness. At stages up to full load mobilisation part of the anchor will be cracked and part uncracked. Predictive equations are developed and an example is provided.

RESUME: Le but de ce texte est d'examiner théoriquement le comportement des tirants scellés ayant des différentes capacités à la force qui provoque les fissures. On examine deux étapes sous l'état de contrainte-allongement: premièrement à partir de l'application initiale de la charge quand le tirant agit comme un corps rigide jusqu'à l'apparition de la première fissure dans la partie scellée du tirant, deuxièmement après l'apparition des fissures perpendiculairement à l'axe longitudinal et leur propagation le long de la partie scellée. Ces cas se distinguent par des valeurs différentes de raideur. Dans les étapes jusqu'à la rupture une partie du tirant va se fissurer e l'autre partie reste intacte. Des formules de prediction sont developpées et un exemple est donné.

An injection anchor under load moves relative to the surrounding soil and mobilizes shear stresses on the lateral surface of its fixed length. In any cross-section of the fixed length a share of longitudinal internal force is neutralised by the acting shear stress τ (Fig.1).

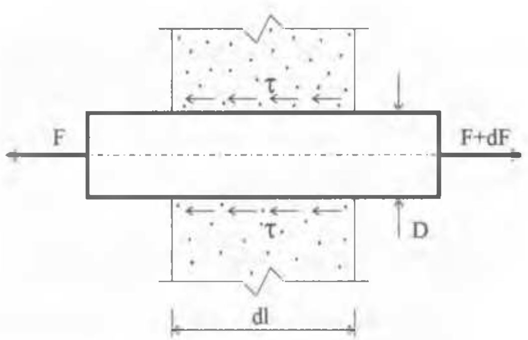

Figure 1. Partial neutralisation of longitudinal inner force by shear stresses acting in any cross-section of the fixed length of an injection anchor.

As a consequence, the displacement u of every following cross-section is less than that of any preceding one. In turn this leads to differential shear stress distribution along the anchorage fixed length in accordance with the relationship between τ and u which has a complex character. Since its analytical evaluation is difficult to allow for when developing a closed-form solution of the engineering method for predicting the load holding capacity, it is convenient to base the deformational analysis of injection anchorages on a simple elasto-plastic relationship as follows [Degil 1989]:

$$\tau = \begin{cases} \tau_{pk}\dfrac{u}{u_f} & \text{when } 0 \le u \le u_f \\ \tau_f & \text{when } u > u_f \end{cases} \qquad (1)$$

u_f being the displacement causing the ultimate shear stress τ_u, τ_f the residual shear stress, τ_{pk} the conditional (on the basis of equivalence of areas bounded by corresponding relationships) ultimate shear stress which is calculated by the formula

$$\tau_{pk} = \frac{1}{u_n}\sum_{i=1}^{n}(\tau_{i-1} + \tau_i)(u_i - u_{i-1}) \qquad (2)$$

τ_i and u_i being the shear stress and displacement, respectively, obtained for the i th increment of load during in-situ testing of anchors (Fig.2). Obviously, the adoption of the above model leads to some distortion in the distribution of shear stresses along the anchor fixed length but it is justified for further transfer to a true τ to u, relationship divided in n segments with straight lines between adjacent points.

1. *Deformational analysis of bearing capacity of ground anchorages at different stages of loading*

Let u_B be the displacement of the 'active' end of an injection anchor, i.e. of point B in Fig.3a where load is transferred from its tendon to its fixed length; L_R the full anchor fixed length; l_f the length of that part of the fixed length on the lateral surface of which the residual shear stress τ_f is mobilised.

Areas within $0YU_f$ and $0ZU_f$ are equal. Uf is the critical displacement (when it is reached by the load transfer point of the anchor root, the critical load shearing capacity is mobilised).

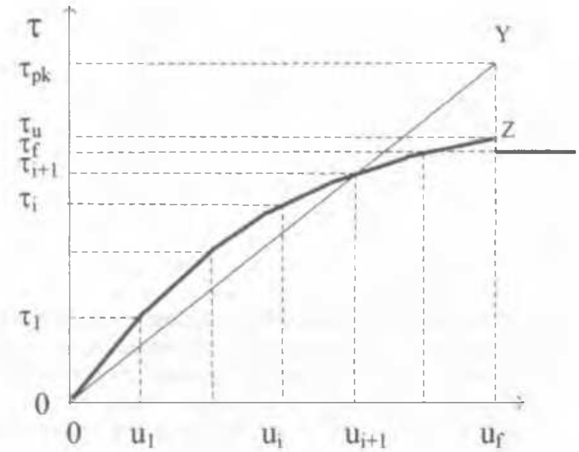

Figure 2. Shear stress - displacement relationship for any specific cross section.

When $0 \le u_B \le u_f$, in any cross-section of the fixed length a share of longitudinal internal force dF neutralised by the acting shear stress τ can be described as

$$dF = \frac{\pi D \tau_{pk}}{u_f} u dl \tag{3}$$

πD being the cross-sectional perimeter of an anchorage fixed length (Fig.1).

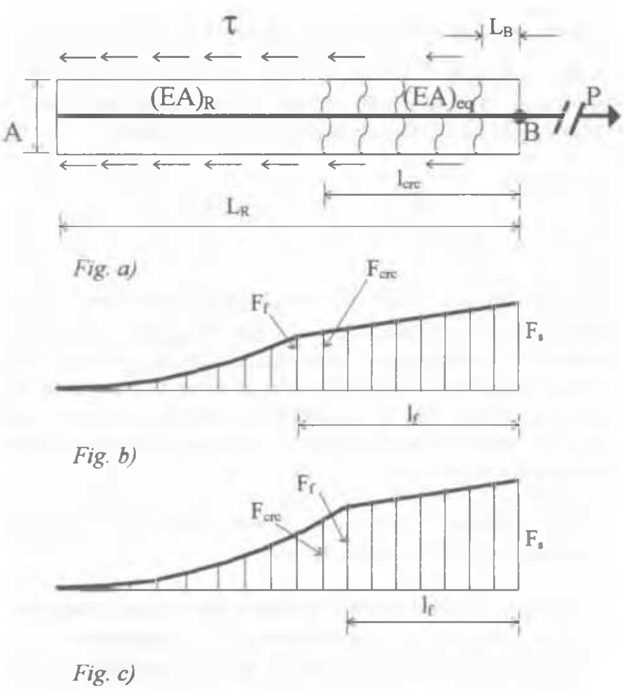

Figure 3. Injection anchor with tension cracks and reduced stiffness along part of its fixed length.

Combining equation (3) and elastic strain $du = Fdl/(EA)$ the following linear homogeneous differential equation with constant coefficients is obtained:

$$\frac{d^2u}{dl^2} - \frac{\pi D \tau_{pk}}{(EA)u_f} u = 0 \tag{4}$$

This needs to be solved taking account of two limits expressed as:

a) $du/dl = 0$ when $l = 0$ (coordinate l is counted from point E in the direction of point B in Fig.3a), and

b) $u = u_B$ when $l = L_R$.

Then a quotient solution of equation (4) can be found in the form

$$u = u_B \cosh(\xi_l)/\cosh(\xi_R) \tag{5}$$

$\xi_l = l\sqrt{\pi D \tau_{pk}/[(EA)u_f]}$ and

$\xi_R = L_R\sqrt{\pi D \tau_{pk}/[(EA)u_f]}$ being the flexibility factors.

Longitudinal internal force distribution along the fixed length of a ground anchor is easily determined if both parts of equation (5) are multiplied by τ_{pk}/u_f and integrated within the limits of 0 to l . For the limiting case of $l = L_R$ the load shearing capacity of an injection anchorage is obtained in the form

$$F_s = \frac{u_B}{u_f}\sqrt{\pi D \tau_{pk}(EA)u_f}\,\tanh(\xi_R) \tag{6}$$

By substituting $u_B = u_f$ in equation (6), the critical load shearing capacity $F_{s,cr}$ is determined:

$$F_{s,cr} = \sqrt{\pi D \tau_{pk}(EA)u_f}\,\tanh(\xi_R) \tag{7}$$

When $u > u_f$, the second limit for finding a quotient solution of equation (4) is $u = u_f$ when $l = L_R - l_f$, and the following relationship can be derived:

$$u = u_f \cosh(\xi_l)/\cosh(\xi_R - \xi_f) \tag{8}$$

$\xi_f = l_f\sqrt{\pi D \tau_{pk}/[(EA)u_f]}$ being the flexibility factor.

Relative values of u determined in accordance with equation (8) are provided in Table 1 for different values of the parameters ξ_R , ξ_f and ξ_l within practical ranges.

A procedure similar to that described above for obtaining equation (6) gives the longitudinal internal force F_f in the cross-section the displacement of which relative to the surrounding soil is equal to u_f :

$$F_f = \sqrt{\pi D \tau_{pk}(EA)u_f}\,\tanh(\xi_R - \xi_f) \tag{9}$$

Then the total load shearing capacity F_s of an injection anchorage is determined by the summation of equation (9) and the force on the rest of the anchor root $\pi D l_f \tau_f$:

$$F_s = \pi D L_R \tau_{pk}\left[\tanh(\xi_R - \xi_f) + \xi_f \frac{\tau_f}{\tau_{pk}}\right] \Big/ \xi_R \tag{10}$$

By differentiating F_s with respect to ξ_f and equating the result to zero, the value of $\xi_{f.u}$ can be derived in the form of

$$\xi_{f.u} = \xi_R - Arc\cosh\sqrt{\frac{\tau_{pk}}{\tau_f}} \geq 0 \qquad (11)$$

and the ultimate load shearing capacity $F_{s,u}$ calculated as

$$F_{s,u} = \pi D L_R \tau_{pk}\left[\tanh(\xi_R - \xi_{f.u}) + \xi_{f.u}\frac{\tau_f}{\tau_{pk}}\right]\Big/\xi_R \qquad (12)$$

The value of $F_{s,u}$, according to equation (12), is presented in dimensionless form in Table 2.

Allowing for compatibility of displacements, it is possible to derive the value of $u_{B.u}$ causing mobilisation of the ultimate load shearing capacity $F_{s,u}$:

$$u_{B.u} = u_f\left\{1 + \xi_{f.u}\left[\tanh(\xi_R - \xi_{f.u}) + 0.5\xi_{f.u}\frac{\tau_f}{\tau_{pk}}\right]\right\} \qquad (13)$$

Relative values of $u_{B.u}$ in accordance with equation (13) are given in Table 3.

2. *Estimation of the propagation of tension cracks along a ground anchorage fixed length and their influence on behaviour*

Generally there may be distinguished two stages of the stress-strain state of injection anchorages in tension (up to the fully mobilised resistance of the surrounding soil): firstly, from the initial application of load to the moment when the first crack appears in the cement body of the anchor fixed length; secondly, after the formation of cracks normal to the longitudinal axis and their propagation along its fixed length. In the former case the anchorage fixed length is sound and elastic with an initial stiffness $(EA)_R$, the behaviour of an injection anchor being described by the formulae derived in Section 1. In the latter case its stiffness is variable: the part in cross-sections of which the value of internal forces is not greater than the crack-forming internal force F_{crc} has the original stiffness $(EA)_R$ whilst the rest of the anchor fixed length has a reduced stiffness $(EA)_{eq}$.

If the crack-forming internal force is not less than the ultimate load shearing capacity of an anchorage, the formation of tension cracks normal to the longitudinal axis of an injection anchor is impossible and the anchor behaves elastically, $(EA)_R$ being its stiffness. The above condition is seldom observed in practice, so the value of $(EA)_{eq}$ needs to be assessed and the following approach seems to be appropriate for this purpose.

Since a crack appears in the cross-section where a longitudinal internal force F reaches the crack-forming force F_{crc}, an external axial load P in excess of F_{crc} is necessary to bring about the process of cracking. It should be emphasized that further mobilisation of the load holding capacity of an anchorage causes the cross-section where $F = F_{crc}$ to move along the fixed length, the number of cracks being dependent on the distance along which cracks have developed and a bobbin length L_b, i.e. the distance between adjacent cracks.

Assuming that cracking stress of set cement mortar, σ, and average bond stress on the lateral surface of the tendon, τ_b , are interrelated, the cracking strength will be overcome at the distance L_b from point B (Fig.3a):

$$L_b = \frac{\sigma\left(\frac{\pi D^2}{4} - n\frac{\pi d_1^2}{4}\right)}{n\pi d_1\tau_b - \pi D\tau_c} \qquad (14)$$

where d_1 and n are the diameter of one element of the tendon assembly and the number of elements, respectively;
τ_c is the mobilised shear stress at the grout/soil interface when $P = F_{crc}$.

Minimum external force required before the first crack appears is equal to the sum of
the cracking strength $X = \sigma\left(\frac{\pi D^2}{4} - n\frac{\pi d_1^2}{4}\right)$ and $\pi D\tau_c L_b$

Formation of every following crack is conditioned by reaching the same magnitude of force in that cross-section where the preceding crack has formed. The process described continues until the moment of mobilisation of the full resistance of the surrounding soil.

A reduced stiffness $(EA)_{eq}$ may be derived on the basis of equivalence of
(1) deformation within the length L_b of the whole cross-section of the anchor root and
(2) elongation of the tendon between adjacent cracks:

$$(EA)_{eq} = \frac{\left(X + \frac{1}{2}\pi D\tau_c L_b\right)n\frac{\pi d_1^2}{4}E_s}{X + \frac{1}{2}\pi D\tau_c L_b(1+k_r) - \frac{1}{4}n\pi d_1\tau_b L_b(1+k_r^2)} \qquad (15)$$

where $k_r = \frac{D}{nd_1}\frac{\tau_c}{\tau_b} < 1$ is the dimensionless factor;
E_s is the elastic modulus of the tendon material.

2.1. *The crack-forming internal force is not less than the critical load shearing capacity and less than the ultimate load shearing capacity of an anchor*

In such a case tension cracks appear when $u_B > u_B^* \geq u_f$, u_B^* being the displacement of the proximal end of an injection anchor at the moment when $F_s = F_{crc}$. The value of u_B^* may be determined by equation (13) in which $\xi_{f.u}$ is replaced by ξ_f^* , in turn this characteristic value being obtained from the solution of the following equation

$$\frac{F_{crc}}{\sqrt{\pi D\tau_{pk}(EA)_R u_f}} = \tanh(\xi_R - \xi_f^*) + \xi_f^*\frac{\tau_f}{\tau_{pk}} \qquad (16)$$

which is derived from the equation $F_{crc} = F_f + \pi D l_f \tau_f$.

If $u_B > u_B^*$ it should be noted that tension cracks do not propagate beyond the length l_f because $F_f \leq F_{s.cr}$
Consequently, the length of that part of the fixed length which has cracks, l_{crc} , is less than l_f at all stages of behaviour (Fig.3b). The flexibility factor $\xi_{crc} = l_{crc}\sqrt{\pi D\tau_{pk}/[(EA)_R u_f]}$ may be calculated by the formula

$$\xi_{crc} = \xi_f - \frac{\tanh(\xi_R - \xi_f)}{\tau_f/\tau_{pk}}\left(\frac{F_{crc}}{F_f} - 1\right) \qquad (17)$$

The unknown value of ξ_f is determined by solving the following equation which is derived making allowance for variability of the stiffness of an anchor fixed length and compatibility of displacements

$$\frac{u_B}{u_f} = 1 + C^2\xi_f\left[\tanh(\xi_R - \xi_f) + \frac{\xi_f}{2}\frac{\tau_f}{\tau_{pk}}\right] - \frac{(C^2-1)\tanh^2(\xi_R - \xi_f)}{2\tau_f/\tau_{pk}}\left[\left(\frac{F_{crc}}{F_f}\right)^2 - 1\right] \tag{18}$$

where $C = \sqrt{(EA)_R/(EA)_{eq}} > 1$ is the dimensionless factor.

By substituting $\xi_{f,u}$ from equation (11) for ξ_f, equation (18) may also be used to find the displacement $u_{B,u}$ corresponding to the ultimate load shearing capacity $F_{s,u}$, the latter being calculated according to equation (12) and presented in dimensionless form in Table 2. The analysis of equation (18) shows higher deformability of the fixed length of an injection anchor with cracks and, as a result of this, greater values of $u_{B,u}$ compared with those based on equation (13) and shown in Table 3. Nevertheless, all force parameters of anchor behaviour such as F_s, $F_{s,cr}$, F_f, $F_{s,u}$ are determined as if the fixed length had no tension cracks. In other words, the anchor fixed length can be considered quasi-sound.

2.2. *The crack-forming internal force is less than the critical load shearing capacity of an anchor*

In such a case tension cracks appear when $u_B < u_f$. The characteristic displacement u_B^* may be derived by equating F_s to F_{crc} in equation (6):

$$u_B^* = u_f\frac{F_{crc}}{\sqrt{\pi D\tau_{pk}(EA)_R u_f}\tanh(\xi_R)} \tag{19}$$

In order to find the relative length ξ_{crc}, the following equation should be solved:

$$\frac{u_B^*\tanh(\xi_R)}{u_B} = \frac{e^{C\xi_{crc}}\tanh(\xi_R - \xi_{crc})}{e^{C\xi_{crc}}\cosh(C\xi_{crc})[1 + C\tanh(\xi_R - \xi_{crc})] - C\tanh(\xi_R - \xi_{crc})} \tag{20}$$

Then the load shearing capacity F_s of an injection anchorage may be calculated by the formula

$$F_s = \begin{cases} \frac{u_B}{u_f}\sqrt{\pi D\tau_{pk}(EA)_R u_f}\tanh(\xi_R) & \text{when } 0 \le u_B \le u_B^*; \\ F_{crc}\left[\frac{u_B}{u_B^*}\frac{\tanh(C\xi_{crc})}{C\tanh(\xi_R)} + \frac{1}{\cosh(C\xi_{crc})}\right] & \text{when } u_B^* < u_B \le u_f. \end{cases} \tag{21}$$

As soon as $u_B > u_f$ (Fig.3c) there are two unknown independent values ξ_{crc} and ξ_f which are determined at any intermediate stage of anchor behaviour (until $\xi_f \le \xi_{crc}$) from the simultaneous solution of the following two equations:

$$\frac{u_B^*}{u_f}\tanh(\xi_R) = \frac{e^{C(\xi_{crc}-\xi_f)}\tanh(\xi_R - \xi_{crc})}{e^{C(\xi_{crc}-\xi_f)}\cosh[C(\xi_{crc}-\xi_f)](1 + C\tanh[\xi_R - \xi_{crc}]) - C\tanh(\xi_R - \xi_{crc})} \tag{22}$$

and

$$\frac{u_B}{u_f} = 1 + C^2\xi_f\left[\frac{\tanh[C(\xi_{crc}-\xi_f)]}{C} + \frac{u_B^*}{u_f}\frac{\tanh(\xi_R)}{\cosh[C(\xi_{crc}-\xi_f)]} + \frac{\xi_f}{2}\frac{\tau_f}{\tau_{pk}}\right] \tag{23}$$

At the moment when $\xi_f = \xi_{crc}$ equation (22) becomes as follows:

$$\frac{u_B^*}{u_f}\tanh(\xi_R) = \tanh(\xi_R - \xi_f^{**}) \tag{24}$$

By solving equation (24) with regard to ξ_f^{**} and substituting this value in equation (23), the characteristic displacement u_B^{**} may be obtained in the form of

$$u_B^{**} = u_f\left[1 + C^2\xi_f^{**}\left(\frac{u_B^*}{u_f}\tanh(\xi_R) + \frac{\xi_f^{**}}{2}\frac{\tau_f}{\tau_{pk}}\right)\right] \tag{25}$$

When $u_f < u_B \le u_B^{**}$ the load shearing capacity F_s of an injection anchorage may be calculated by the formula

$$F_s = F_{crc}\left[\frac{u_f}{u_B^*}\frac{\tanh[C(\xi_{crc}-\xi_f)]}{C\tanh(\xi_R)} + \frac{1}{\cosh[C(\xi_{crc}-\xi_f)]} + \frac{u_f}{u_B^*}\frac{\xi_f}{\tanh(\xi_R)}\frac{\tau_f}{\tau_{pk}}\right] \tag{26}$$

When $u_B > u_B^{**}$ there is no need for the simultaneous solution of equations (22) and (23), ξ_f being determined by solving equation (18). Then the load shearing capacity F_s of an injection anchor is calculated according to equation (10) and the situation described in Section 2.1 is realised.

The parametric analysis of the proposed method for estimating the propagation of tension cracks along an anchor fixed length shows higher deformability of the injection anchor fixed length with decrease in the crack-forming internal force. When the crack-forming internal force is less than the ultimate load shearing capacity of an injection anchorage, additional corrosion protection measures should be provided or, alternatively, anchors in which the fixed length is compressed under loading can be considered.

EXAMPLE

Consider an injection anchor with the fixed length working in tension. Let L_R be equal to 7.5 m, D = 0.17 m, $(EA)_R$ = 385 MN, $(EA)_{R,crc}$ = 228 MN, U_f = 4.27 mm, τ_{pk} = 77.6 kPa, τ_f/τ_{pk} = 0.9. Then $\xi_R = L_R\sqrt{\pi D\tau_{pk}/[(EA)u_f]} = 1.191$,

$\xi_{f,u} = \xi_R - Arc\cosh\sqrt{\tau_{pk}/\tau_f} = 0.864$ and

$C = \sqrt{(EA)_R/(EA)_{R,crc}} = 1.3$.

Table 1. *Displacements distribution along the fixed length of an injection anchor*

$\xi_R - \xi_f$	Variation of U/U_f (U/U_B if $l_f = 0$) when $l/(L_R - l_f)$ is									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	1	1	1	1	1	1	1	1	1	1
0.2	0.981	0.981	0.982	0.983	0.985	0.987	0.990	0.993	0.996	1
0.4	0.926	0.928	0.932	0.937	0.944	0.952	0.962	0.973	0.986	1
0.6	0.845	0.850	0.857	0.868	0.882	0.899	0.919	0.943	0.970	1
0.8	0.750	0.757	0.769	0.786	0.808	0.836	0.868	0.906	0.950	1
1.0	0.651	0.661	0.677	0.701	0.731	0.768	0.813	0.867	0.929	1
1.5	0.430	0.444	0.469	0.504	0.550	0.609	0.682	0.770	0.875	1
2.0	0.271	0.287	0.315	0.355	0.410	0.481	0.572	0.685	0.826	1
3.0	0.104	0.118	0.142	0.180	0.234	0.309	0.412	0.552	0.742	1
5.0	0.015	0.021	0.032	0.051	0.083	0.136	0.223	0.368	0.607	1
10.			0.001	0.002	0.007	0.018	0.050	0.135	0.368	1

Table 2. *Relative values of the ultimate load shearing capacity of an injection anchor*

ξ_R	Variation of $F_{s,u}/(\pi D L_R \tau_{pk})$ ratio when τ_f/τ_{pk} is equal to									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	1	1	1	1	1	1	1	1	1	1
0.2	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	1
0.4	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.954	1
0.6	0.895	0.895	0.895	0.895	0.895	0.895	0.895	0.904	0.936	1
0.8	0.830	0.830	0.830	0.830	0.830	0.831	0.846	0.878	0.927	1
1.0	0.762	0.762	0.762	0.762	0.766	0.785	0.817	0.862	0.922	1
1.5	0.603	0.604	0.616	0.641	0.678	0.723	0.778	0.841	0.914	1
2.0	0.483	0.503	0.537	0.581	0.633	0.693	0.759	0.831	0.911	1
3.0	0.356	0.402	0.458	0.521	0.589	0.662	0.739	0.821	0.907	1
5.0	0.253	0.321	0.395	0.472	0.553	0.637	0.723	0.812	0.904	1
10.	0.177	0.261	0.347	0.436	0.527	0.619	0.712	0.806	0.902	1

Table 3. *Relative values of displacement $U_{B,U}$ causing mobilisation of the ultimate load shearing capacity*

ξ_R	Variation of $U_{B,U}/U_f$ ratio when τ_f/τ_{pk} is equal to									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	1	1	1	1	1	1	1	1	1	1
0.2	1	1	1	1	1	1	1	1	1	1.02
0.4	1	1	1	1	1	1	1	1	1.03	1.08
0.6	1	1	1	1	1	1	1	1.06	1.12	1.18
0.8	1	1	1	1	1	1.04	1.11	1.18	1.25	1.32
1.0	1	1	1	1	1.09	1.18	1.26	1.34	1.42	1.50
1.5	1	1.05	1.26	1.41	1.53	1.65	1.76	1.87	1.99	2.13
2.0	1.17	1.53	1.76	1.94	2.10	2.27	2.43	2.60	2.79	3.00
3.0	2.19	2.63	2.98	3.30	3.62	3.95	4.30	4.66	5.06	5.50
5.0	4.53	5.45	6.33	7.22	8.15	9.12	10.13	11.19	12.30	13.50
10.	12.11	15.97	19.94	24.03	28.24	32.55	36.97	41.50	46.16	51.00

Calculations of the ultimate load shearing capacity and corresponding displacement of the "active" end of the anchor fixed length, according to equations (12) and (13), give $F_{S,U}$ = 285 kN and $U_{B,U}^{(1)}$ = 6.87 mm, respectively. For illustration let the crack-forming internal force have three values, namely $F_{crc}^{(1)}$ = 300 kN, $F_{crc}^{(2)}$ = 250 kN, $F_{crc}^{(3)}$ = 200 kN.

If $F_{crc} = F_{crc}^{(1)}$ = 300 kN, tension cracks do not appear owing to this value being in excess of the value of $F_{S,U}$.

If $F_{crc} = F_{crc}^{(2)}$ = 250 kN, equations given in Section 2 of this Paper are valid due to $F_{s,cr}$ = 217 kN ≤ $F_{crc}^{(2)}$ = 250 kN < $F_{s,u}$ = 285 kN, $F_{s,cr}$ being calculated by equation (7). The values of ξ_f^* and U_B^* relevant to the condition $F_s = F_{crc}^{(2)}$ are expressed as ξ_f^* = 0.243 and U_B^* = 5.15 mm. The ultimate load shearing capacity $F_{s,u}$ = 285 kN is realised when $U_{B,U}^{(2)}$ = 7.32 mm and $\xi_{crc,u}$ = 0.151 (i.e. $l_{crc,u}$ = 0.95 m), according to equations (18) and (17) respectively.

If $F_{crc} = F_{crc}^{(3)}$ = 200 kN, tension cracks appear when $U_B > U_B^*$ = 3.94 mm, U_B^* being calculated by equation (19). The next three stages of anchor behaviour that deserve to be mentioned are as follows:-

a) when $U_B = U_f$ = 4.27 mm the values of ξ_{crc} = 0.046 and $F_{s,cr}$ = 212 kN are determined in accordance with equations (20) and (21), respectively;
b) equations (24), (25) and (26) give ξ_f^{**} = 0.180, U_B^{**} = 5.37 mm and F_s = 242 kN respectively;
c) the ultimate load shearing capacity $F_{s,u}$ = 285 kN is realised when $U_{B,U}^{(1)}$ = 7.87 mm and $\xi_{crc,u}$ = 0.364 (i.e. $l_{crc,u}$ = 2.29 m), according to equations (18) and (17) respectively.

APPLICATION

The predictive equations proposed for estimating and calculating the length subject to the propagation of tension cracks along an anchorage fixed length have been verified during the construction of the Minsk Metro. In several field tests with subsequent exhumation of anchors it has been found that some 80% of the anchor fixed length had cracks perpendicular to a single bar tendon. The results of one particular analysis for predicting the process of cracking are given below, with the input parameters necessary being adopted as follows:-

- the 7.5 m fixed length of 170 mm diameter has $(EA)_R$ and $(EA)_{eq}$ values of 385 MN and 228 MN respectively;
- the ultimate shear stress of 77.6 kPa is achieved at the displacement of 4.27 mm; and
- the crack-forming internal force was assessed to be 33 kN.

Displacement, mm, of the proximal end of the anchor fixed length	Length, m, of propagation of tension cracks along the fixed length from its proximal end
0.6	0.00
1.2	2.22
1.8	3.56
2.4	4.38
3.0	4.93
3.6	5.31
4.2	5.60

CONCLUSION

The presence of cracking, although influencing the load-displacement characteristics of injection anchorages, is not considered to be important for temporary anchors, but it is relevant in the long term conditions where additional corrosion protection measures should be provided unless the geometry of an anchor can be altered so that its fixed length works wholly in compression.

REFERENCE

Degil, G.O (1989) Injection Anchors deformational analysis, taking account of the formation of their fixed lengths in soil. PhD thesis, Belarusian Polytechnic Institute.