In-situ tests of permanent prestressed ground anchors with alternative designs of anchor bond length

Essais in situ des tirants d'ancrage précontraints permanents avec des conceptions alternatives de la longueur de scellement

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ABSTRACT: Some concepts of cost efficient ground anchors with enhanced pull-out resistance from single borehole already exist: single bore multiple anchors (Barley, 1990) and prestressed ground anchors of variable stiffness (Škrabl, 2004). A third alternative with anchor bond length of increased stiffness has been proposed. All three concepts have been combined with the concept of comprehensive corrosion protection. Five anchors of all three design alternatives as well as ten investigation tests on standard permanent prestressed ground anchors were tested in-situ on a large retaining wall in N-E Slovenia. The paper presents the design of each type of anchor bond length, test procedure and test results. The test results of our in-situ research on the specific location show that the highest anchor pull-out resistance was obtained for the anchor bond length of increased stiffness.

RÉSUMÉ: En plus des conceptions existantes d'augmentation de la résistance des tirants d'ancrage dans un même forage avec un bon rapport coûts-efficacité, tels les tirants à torons multiples (technologie SBMA – Barley, 1990) et les tirants précontraints de rigidité variable (Škrabl, 2004), nous proposons une troisième alternative: les tirants d'ancrage à rigidité renforcée. Les trois types étudiés ont été combinés parallèlement avec une conception de protection anti-corrosion. Nous avons testé in situ des ensembles de cinq groupes de chacun des trois types proposés et de dix tirants d'ancrage standard, sur une construction de soutènement importante réalisée dans la partie nord-est de la Slovénie. Dans cet article nous présentons le dimensionnement de la longueur de scellement de tous les types de tirants d'ancrage ainsi que le déroulement et les résultats des essais effectués. Les résultats des essais in situ démontrent que la résistance maximale est obtenue avec la longueur de scellement du tirant à rigidité renforcée.

KEYWORDS: ground anchor, design of bond length, pull-out resistance, in-situ test, comprehensive corrosion protection.

1 INTRODUCTION

In 1934 the first prestressed ground anchors were built during the raising of the Cheurfas Dam (Algeria). Such anchors have been increasingly used since then, in cases, where the execution of other geotechnical measures is significantly more difficult, more expensive or even impossible. The most widespread is the use of the friction tensile type of ground anchors (Limelette, 2008), with which the technological design and implementation of the corrosion protection has reached a level that promises a long-term operation (provided that adequate maintenance is ensured). This especially applies to anchors with a comprehensive corrosion protection, which was two decades ago developed in Switzerland: the steel parts of these anchors are encapsulated by a waterproof polyethylene (PE) cover, which also provides electrical isolation of steel parts against the environment. In parallel with technological improvements, the price of anchors has also grown. Therefore, increasing tendencies to rationalize anchors have appeared.

Three different simple modifications of a permanent prestressed anchor bond length were designed and investigated in order to achieve higher values of pull-out resistances and better efficiencies of anchors. The prototypes of such alternative anchors were installed and tested in a testing field. The obtained results were compared with those of reference anchors.

2 ALTERNATIVE DESIGNS OF BOND LENGTHS

The starting-point in the task of searching for the most effective concept of permanent prestressed ground anchors with the tendon contained within joint PE cover were reference (standard) anchors **RCP/D**. These anchors were used in a retaining wall that served as a test site. The total length of each individual anchor is l = 35 m with the tendon bond length of l_v = 7 m, consisting of six low-relaxation strands ∅ 15.2 mm ($f_{p0.1k}/f_{pk}$= 1670/1860 MPa).

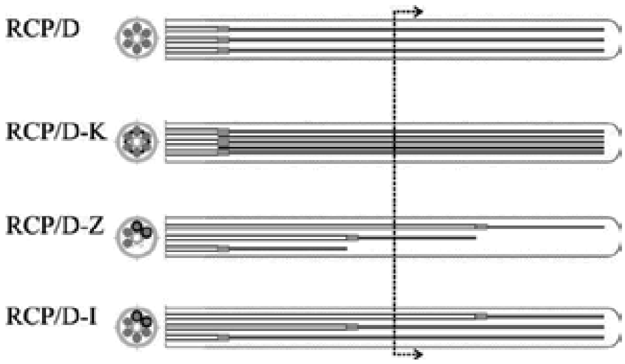

Figure 1. Conceptual designs of bond lengths of permanent prestressed strand anchors with joint PE encapsulation: reference anchor RCP/D, alternative types of anchors RCP/D-K (increased stiffness of bond length), RCP/D-Z (multiple anchor) and RCP/D-I (anchor of variable stiffness).

Three different conceptual designs of anchor bond lengths (Fig. 1) were conceived and implemented with the intention to improve stress distribution along the tendon bond length and to consequently increase the pull-out capacity of anchors:

- *anchors with increased stiffness of bond length*, with which six additional steel wires ∅ 5 mm were placed in empty spaces among bond lengths of strands (type **RCP/D-K** with strand free lengths of 28 m and strand bond lengths of 7 m),
- *multiple anchors with staggered anchor units* based on the idea of Barlay's anchors SBMA, only that three anchor units

(two strands each) of 2.2 m bond length were not installed into a borehole as independent elements but were placed into the joint corrugated PE duct (type **RCP/D-Z** with strand free lengths of 28 m, 30.4 m and 32.8 m),

- *anchors with variable stiffness of bond length* after the patent of Škrabl, 2004, with the tendon combined of three anchor units (2 strands each), with strand free lengths of 28.0 m, 30.4 m and 32.8 m, and with strand bond lengths of 7.0 m, 4.6 m and 2.2 m (type **RCP/D-I**).

3 IN-SITU TESTING

The test field has been located at the level of the middle berm of a larger retaining wall, where load-bearing stratum consists of marl and silty marls with thin lenses of siltstone and sandstone. A total of 18 anchors were installed: three reference RCP/D anchors and five anchors of each alternative type (RCP/D-K, RCP/D-Z and RCP/D-I). Boreholes, deflected 15° downwards, were drilled with a chisel (∅ 140 mm) using air-flushing for the removal of drill spoil. The ratio of 6-strand anchor steel cross-sectional area to cross-sectional area of the borehole equaled 5.5% of the theoretical cross-sectional area of the borehole. The appearance of moist in the ground was repeatedly detected in the region of the anchor bond lengths. Cement grout with w/c ratio of 0.42 was used for grouting within the PE encapsulation as well as for the collar of the borehole with an average grout consumption of about 17 dm^3/m^1.

At in-situ testing individual strands were tensioned with monostrand jacks, connected to a joint hydraulically synchronized system (Fig. 2). An electrical load cell was used for the precise adjustment of stressing forces. Extensions and creep behavior of strands were measured with digital displacement transducers, attached on the monostrand jacks.

Figure 2. Test setup for simultaneous stressing of all strands of prestressed ground anchors using monostrand jacks.

As a measure for the assessment of load-bearing characteristics of anchor bond lengths creep displacement rate k was used (Ostermayer, 1975):

$$k = \frac{s_2 - s_1}{\log t_2/t_1} \quad (1)$$

where s_1 and s_2 are head displacements at times t_1 and t_2, respectively. For the failure of anchor bond length the critical creep displacement rate k_{crit} = 2 mm was used.

All reference anchors and one anchor of each alternative type were tested up to the maximum test load P_{pv} = 1254 kN (80 % steel tensile strength R_m) or until failure of anchor bond length was reached (*investigation test* - IT). Other alternative anchors were tested using the same procedure, except that the test was stopped at the first sign of anchor bond length failure, i.e. as soon as k_{crit} appeared (*comprehensive suitability test* - CST). All test field anchors were tested according to the loading procedure and methodology for IT as described in Swiss standard SIA 267/1, which is very similar to test Method 1 of standard EN 1537: each anchor was loaded in eight incremental cycles from a datum load P_a = 150 kN (10 % R_m) to the maximum test load P_{pv}. The increments of strand extensions were measured at the end of specified time intervals, which were used for the evaluation of k values. Individual strand extensions as well as average extensions for all strands of the RCP/D-I anchor SBZ-33 at load level P_6 = 978 kN of CST are presented on the left diagram of Fig. 3. The right diagram shows the development of apparent free lengths l_f of individual strands during the same CST, which is based on the measured elastic displacement Δs_{el} at load decreasing from current level P_i to the initial level P_a, knowing the characteristics of the tendon (cross-section area A_p and modulus of elasticity E_p):

$$l_f(P_i) = \frac{\Delta s_{el}}{P_i - P_a} A_p E_p \quad (2)$$

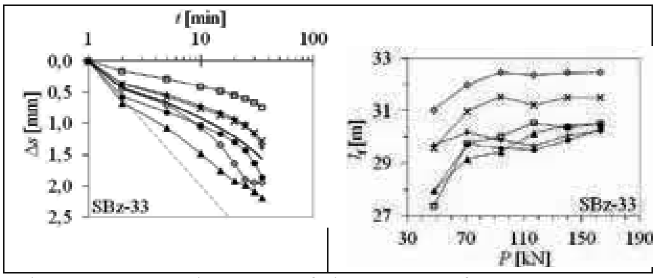

Figure 3. Measured increments of displacements of the anchor SBz-33 (type RCP/D-I) at load level P_6 of CST (left), apparent free lengths of individual strands l_f during CST (right).

The behaviour characteristics of anchor bond length could be recognized only on the basis of strand extensions, measured on displacement transducers, fixed on the monostrand jacks. The problem is that due to the limited amount of data and the inability of physical insight into the bond lengths deep in the load bearing stratum, we cannot always directly link measured extensions with creep displacement rate k of the bond length (i.e. it is not necessary that each measured strand extension actually originates from the bond length deterioration). Therefore, in the analysis of the in-situ test results it is recommendable to compare the k values of individual strand with the k values of other individual strands of the same tendon, with k values of anchor units (average of two strands, only at types RCP/D-Z and RCP/D-I), with the average k values of all strands, as well as with the permanent displacements Δs_{bl} and apparent free lengths l_f, obtained after each loading stage. In order to prevent sudden failures of bond lengths at CST, an appropriate software tool was prepared to enable simultaneous recording and evaluation of the most important behaviour parameters of an anchor during in-situ test.

4 ANALYSIS OF RESULTS OF THE IN-SITU TESTING

There are several possible failure mechanisms at the anchor bond length, which occur at the IT of prestressed ground anchor with a comprehensive corrosion protection: inside or outside the PE corrugated duct, under some circumstances it may also come to the rupture of PE duct. The types and incidences of individual mechanisms depend on the design of bond length and packing connections at the transition between strand free and bond lengths, possible surface contamination of the bare strand bond length, the design, dimensions and distribution of the constituent components of anchors, local conditions in the ground, configuration of strands in the bond length, drilling and flushing techniques as well as specifics of grouting. According to the principle of the weakest link in the chain, there starts a mechanism that occurs at the lowest load level, although in the following load steps some additional mechanisms may also occur.

The bond lengths (2.2 m) of the shortest anchor units (RCP/D-Z and RCP/D-I anchors) were determined according to the available anchor bond length 7 m and previous experience (Barley and Windsor, 2000, Bruce et al., 2007). The bare strands of the bond length of RCP/D and RCP/D-K anchors were spirally rotated along the longitudinal axis, while the strands of the short bond length of RCP/D-Z and RCP/D-I anchors were straight. The bare strands of the bond length of RCP/D anchors (and to a certain extent of RCP/D-K anchors) were additionally arranged in a pattern of alternating spatial extension and compression of strands. Although the lengths of strand bond lengths were selected in accordance with the aforementioned recommendations, the analysis of the in-situ test results of RCP/D-Z and RCP/D-I anchors showed predominant mechanism of pull-out of strands bond length from cement grout inside the corrugated PE duct. Such behavior can be associated with the greasing technology of strand free length, in which some strands in bond lengths can be locally stained with vaseline, although most of the stains were later on removed. Contrary to expectations, only in individual cases of RCP/D and RCP/D-K anchors, there appeared the pull-out mechanism of the whole tendon from the cement grout inside corrugated PE duct. Such behaviour can be partly ascribed to the local contamination of bare strands with vaseline stains, and partly to the direct contact of strand bond lengths with the bottom part of the corrugated PE duct (no minimum grout cover was provided).

The behaviour of anchor bond length is reflected in the most important outcome of the IT: pull-out resistance R_a, which is determined as the intersection of experimentally obtained curve of interval creep displacement rate k_{int} to the assumed margin that denotes the failure of an anchor k_{crit} = 2 mm. In cases where such intersection does not exist, the failure of anchor bond length is not reached – in these cases the standard SIA 267/1 allows for an extrapolation of R_a as a proof load extrapolated up to 10%. The problem with this assessment remains when the anchor bond length can be assessed as failed, or in other words, in those cases when it is a reasonable to expect that the anchor bond length would be able to sustain a load of 1.10 P_{pv}. The analysis of in-situ obtained test results for the considered type of anchors showed: if the following criteria are satisfied, this could be a suitable basis for 10 % extrapolation of P_{pv}, provided that the estimate is made by an experienced specialist:

- linear trend approximation of the creep displacement rates at the proof load P_{pv} (considering all strands and the anchor as a whole) should not exhibit any noticeable increase in creep rate,
- maximum creep displacement rate in each time interval after the second minute of observation (for each strand and the anchor as a whole) must not exceed the criterion of failure k_{crit},
- the interval creep displacement rate k_{int} (P_{pv}), of each strand and the anchor as a whole should not be greater than 1.35.

Results of all performed in-situ tests are presented as values of pull-out resistances R_a [kN] (Table 1) as well as in the diagrams of interval creep displacement rates k_{int} obtained at all stages of IT and CST (Fig. 4).

The general impression in the ratio of pull-out resistances among various types of tested anchors can already be obtained on the basis of visual assessment of the curves in the diagrams: the highest values of anchor bond length resistance (i.e. high loads P reached at low values of k_{int}) were achieved at RCP/D-K anchors with increased stiffness of bond length, which slightly exceeded the bond length resistance of reference RCP/D anchors. An unexpectedly rapid failure of two reference RCP/D anchors was a result of problems at grouting (anchor SBz-23) and distinctive slip of two strands, probably due to bare strand contamination with vaseline (anchor SBz-59). On the other hand, multiple anchors with staggered bond lengths (RCP/D-Z type) demonstrated the poorest performance of all tested anchors due to early failure of bond lengths at low load stages of IT or CST (deterioration of bond between strands and cement grout resulted in the pull-out of the strands). The behaviour of RCP/D-Z and RCP/D-I anchors was probably influenced by the surface contamination with vaseline as well as configuration of strands in the bond length. Additional impairment of the conditions within the corrugated PE duct was caused by the use of soft and relatively spacious packing connections in the transition between anchor unit bond and free length.

Table 1. Results of in-situ tests: pull-out resistances R_a [kN] of all tested anchors of reference and alternative types.

RCP/D		RCP-D/K		RCP-D/Z		RCP-D/I	
Anchor	R_a [kN]	Anchor	R_a [kN]	Anchor	R_a [kN]	Anchor	R_a [kN]
TS-01*	800	SBz-89*	1254	SBz-56*	702	SBz-86*	1144
TS-02*	979	SBz-18#	978	SBz-36#	694	SBz-12#	604
TS-03*	981	SBz-39#	1231	SBz-63#	469	SBz-33#	1248
TS-04*	1015	SBz-66#	1220	SBz-81#	837	SBz-60#	789
TS-05*	1095	SBz-84#	978	SBz-15#	400	SBz-78#	840
TS-06*	1195						
TS-07*	1227						
SBz-23*	651						
SBz-56*	1211						
SBz-59*	642						

*… Result of IT.

#… Result of CST.

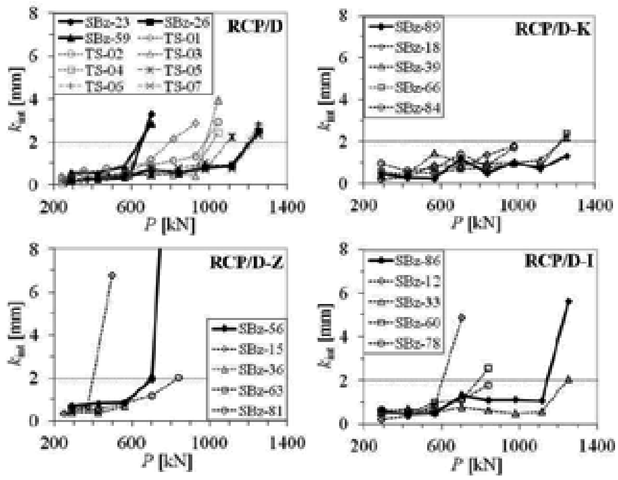

Figure 4. Interval creep displacement rates k_{int} for reference testing anchors as well as for all types of alternative anchors.

To confirm the relationships among pull-out resistances R_a (Table 1) a one-sided Student's T-test with unequal variance was used to check whether the average values of different types of anchors differ significantly from each other.

Results of testing the hypothesis of the equality of the means of two normal populations at the 5 % significance level showed that the mean value of RCP/D-Z anchor pull-out resistance was statistically typically lower than the mean values of pull-out resistance of reference RCP/D and alternative RCP/D-K anchors (Table 2). Somewhat unexpectedly, using statistical methods we could not confirm that the mean value of RCP/D-Z anchor pull-out resistance was statistically typically lower than the mean value of pull-out resistance of RCP/D-I anchors, as it could be inferred only on the basis of visual comparison of the curves in the graphs in Fig. 4.

Table 2. Results of one-sided Student's T-test with unequal variance of mean pull-out resistances R_a for reference and alternative anchors.

	RCP/D	RCP/D-K	RCP/D-Z	RCP/D-I
Mean	980	1132	620	925
Variance	47770	19965	32622	70263
Standard deviation	218,6	141,3	180,6	265,1
Coef. of variation	0,223	0,125	0,291	0,287
RCP/D	–			
RCP/D-K	13,0 %	–		
RCP/D-Z	**0,7 %**	**0,1 %**	–	
RCP/D-I	70,3 %	17,3 %	7,1 %	–

5 CONCLUSIONS

Based on the theoretical background of bond length behaviour of a prestressed ground anchor and the patents of Barley and Škrabl, three types of anchors with alternative concepts of bond lengths inside PE encapsulation (RCP/D-K, RCP/D-Z and RCP/D-I types) were designed, installed and tested at a test field. The behaviour of alternative types of anchors was compared with the behaviour of the reference RCP/D anchors. Different aspects of design (especially limited anchor bond length of 7 m, the diameter of available type of corrugated PE duct), formation, manufacturing details and installation of testing field anchors resulted in different pull-out resistances R_a and they indicate the relations among bond length capacities of different anchor types.

Test results of 25 anchors showed that the maximum values of pull-out resistance R_a were reached at the modified RCP/D-K anchors with increased stiffness of bond length - the mean values of R_a of RCP/D-K anchors exceeded the mean values of R_a of RCP/D anchors by 16 %. Although the free space within the corrugated PE duct of bond length of the RCP/D-K anchors was very restricted, allowing only ∅ 5 mm additional steel wires to be installed (instead of originally planned ∅ 12.5 mm steel strands), high values of pull-out resistances of RCP/D-K anchors were obtained. The behaviour of RCP/D-Z and RCP/D-I anchors was probably influenced by the surface contamination with vaseline as well as the configuration of strands in the bond length. Additional impairment of the conditions within the corrugated PE duct was caused by the use of soft and relatively spacious packing connections in the transition between anchor units bond and free length. The RCP/D-Z anchors demonstrated the poorest performance of all tested anchors (the bond length of RCP/D-Z anchors failed at low force levels of IT and CST). In all cases local debonding at the strand/grout interface resulted in the pull-out of strands. With improvement of particular technological details of alternative anchors, higher values of pull-out resistances can be expected. According to the experiences of Barley with multiple anchors, the pull-out resistances of RCP/D-Z anchors should attain (and probably exceed) the pull-out resistances of reference RCP/D anchors, provided that the pull-out of strands from cement grout, placed within the corrugated PE duct, is prevented. At least it is necessary to provide the immaculate condition of bare strands in the bond length within the PE encapsulation. Moreover, it is also possible that instead of RCP/D-K anchors the highest values of pull-out resistance could be achieved at one of the other alternative types (RCP/D-I or RCP/D-Z).

With the intention to increase the efficiency of alternative types of permanent prestressed anchors (RCP/D-K, RCP/D-Z and RCP/D-I) the following improvements are suggested:

- Results of field testing confirm the already known fact (Littlejohn, 1993, Hanna, 1982) that for effective performance of bond length the bare strands should be covered with sufficiently thick layer of cement grout, irrespective of the anchor bond length design.
- The efficiency of anchor bond length could be improved with the increase of corrugated PE duct diameter. In that case the region around bare strands within corrugated PE duct could be reinforced (spiral micro reinforcement, cement grout with admixed fibres, etc.). Simultaneously, extra space would be gained for noding or local deforming of strands.
- The efficiency of RCP/D-Z and RCP/D-I anchors could also be improved by upgrading the technological detail of anchor unit packing connections at the transition between strand bond and free lengths. Performance of RCP/D-z and RCP/D-I anchors could also be improved if the greased and sheathed strands in the free length would possibly be replaced with some other solution that offers higher stiffness in radial direction.
- For specific design of RCP/D-Z and RCP/D-I anchors the combination of strand and anchor unit noding is suggested, whereat the minimal anchor unit strands bond length should be 2.5 m (in case of the increased diameter of corrugated PE duct) and 3.0 m (in case of the unchanged diameter of corrugated PE duct).

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