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Research paper

Single Bore Multiple Anchors – conclusions based on anchor tests

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Abstract: The technology of single bore multiple anchor is well known and mainly used as a method of providing support for retaining walls of deep excavations in weak soils. Multiple fixed lengths in a single borehole is a major difference to conventional anchors. The purpose of it and the most important facts affecting bearing capacity are presented. Due to the reduction of progressive debonding higher bearing capacities can be achieved and the impact of soil consolidation is decreased. Unique properties of this technology potentially reduce construction costs and increase the reliability and safety of the structure. Single Bore Multiple Anchors in most cases are prestressed by synchronised hydraulic jacks to provide that every anchor unit transfers the same load. The purpose of this paper is to present the results of investigation and suitability tests, which took place at the site of Zlote Tarasy Shopping Centre in Warsaw. The carried out research reveals that prestressing of one fixed anchor causes a decrease in lock-off load of the second fixed anchor, regardless of the order of prestressing. Measured values presents range from 6% to 14%. Results indicate mutual influence between loads of fixed anchors from the separate prestressing.

Keywords: ground anchors, single bore multiple anchor, deep excavation, bearing capacity of ground anchor

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1. Introduction

Urban areas are tightly packed with new buildings and underground infrastructure, any new development in this area has impact to already existing ones [1, 2]. The urbanization and its height and depth is increasing constantly. One of the design challenges is a proper deep excavation walls support, what is a subject of many analyses of appropriate soil modelling [3, 4] or calculation methods [5]. Retaining structures in urban areas have to meet strict requirements for capacity and acceptable displacement. Ground anchors are most often as a support of these structures [6, 7]. Less common, the role of ground anchors is to ensure the stability of landslides or foundation slabs in high groundwater pressure conditions [8, 9]. In both cases, the failure of an anchor in temporary or permanent phase is potentially catastrophic for the structure and its users.

Due to increasing requirements for conventional ground anchors, the technology of single bore multiple anchors (SBMA) was developed. These structures are designed to fulfill the demanding design requirements for high bearing capacities, even in weak soils or weak rocks [10, 11], as a permanent or temporary supports [12–14]. In cohesive soils SBMA anchors are able to achieve failure loads of 2000 to 3000 kN [15], what is an unreachable result for typical ground anchors.

2. Technology of Single Bore Multiple Anchor system

2.1. The idea of multiple anchors

Single Bore Multiple Anchors are technological improvement of conventional ground anchors. By definition, also those structures are designed to transfer tensile forces into the soil, but differences in construction, range of application, design and execution details exist. As the name suggests, these anchors have multiple anchor units (fixed lengths) in a single borehole.

The purpose of using this technology is to reduce the effect of progressive debonding – a phenomenon associated with non-uniform distribution of bond stress along the fixed length under the load [15–18]. It is well known that bearing capacity of an anchor does not increase proportionally to length of the fixed length. Due to progressive debonding a significant part of the load is transmitted to the soil by a small part of fixed length, when the rest transfers only a small part of the load [19, 20] (Fig. 1).

As a result the anchor works less efficiently as its fixed length gets longer. Thus, it is logical and economically reasonable to use multiple short bond lengths, where the impact of progressive debonding is negligible, to allow soil to be used in the most efficient way.

Simple estimation of bearing capacities of conventional anchor, 2-unit and 3-unit SBMA anchors, with Barley's formula for efficiency factor in cohesive soils shows its significant increase, despite the total fixed length is the same (Fig. 2) [15, 21].

Comparing materials usage of two anchor types, one SBMA anchor and one conventional anchor, of the same diameter, borehole length and total fixed length, small differences

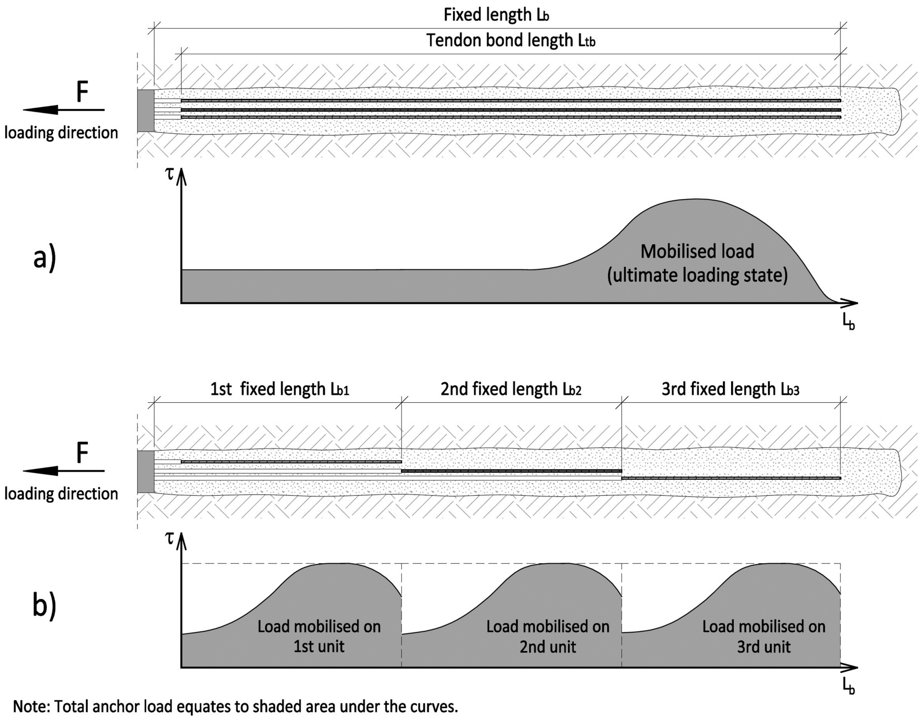

Fig. 1. Comparison of the load distribution in: a) normal anchor fixed length and b) in single bore multiple anchor [21]

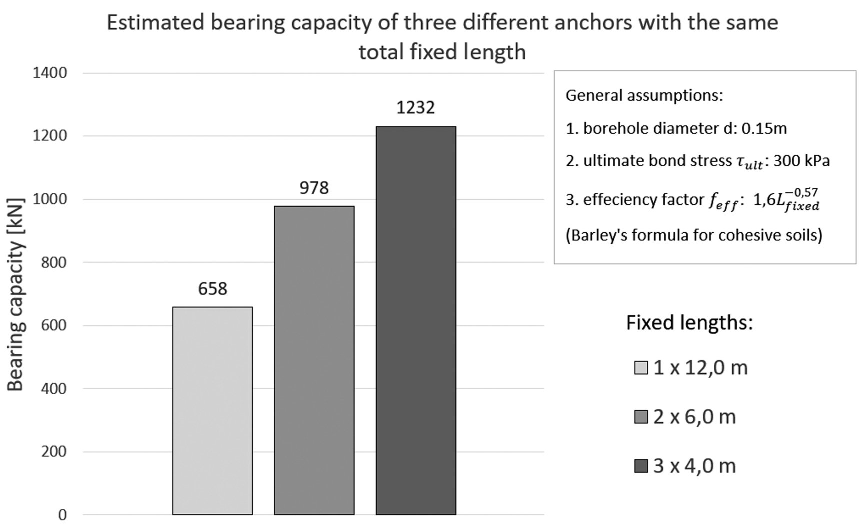

Fig. 2. Estimation of bearing capacities of different anchors with the same total fixed length

can be observed. Proximal unit tendons ends first and only tendons of the distal unit reach the end of the structure. Due to that SBMA anchor may be considered as more economical, because total tendons length is reduced (approximately 4 meters) with each anchor unit made. In both compared cases, the volume of grout is the same.

Several independently operating anchor units increase the reliability of the structure. In case of random incidents, execution mistakes or failure of one anchor unit, the others are able to partially overload, what reduces the risk of sudden failure of whole structure [21].

Considering the execution of a structure, the biggest difficulty is a prestressing process. The main difference is that all tendons cannot be prestressed at the same time with the same stressing jack. To provide an equal load distribution, the proximal and distal tendon groups must be prestressed individually, because of different free lengths. Due to that at least two synchronized stressing jacks are recommended [21]. More complex prestressing process is a potential reason why the technology of SBMA is less popular compared to conventional anchors.

2.2. Short history of SBMA

Despite the fact that the non-uniform distribution of bond stress along the fixed length was acknowledged [20] there is no information in the literature about the application of single bore multiple anchor system in its currently known form before 1988. Research performed in the late 1970s indicated that the transfer of load to the soil could be done more efficiently. One of the first investigations to confirm that short anchor elements were capable of transferring force between the tendon, fixed length and soil was carried out in 1978 by A.D. Barley [22].

In 1987 Greenwood and McNulty published a report on shear tube anchors. System which transfers the load by multiple concentric tubes retained by a compression fitting. Elements are located on the end of debonded strands in one pregrouted encapsulation (Fig. 3).

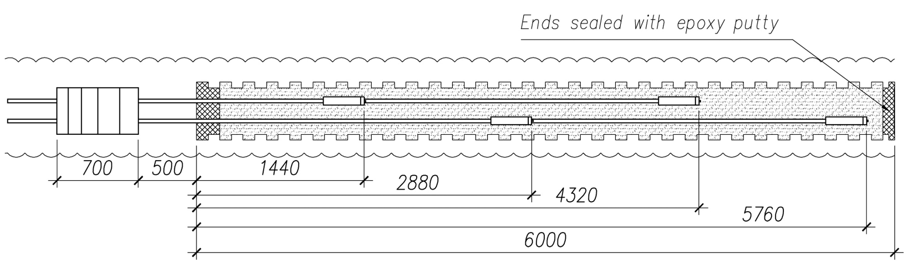

Fig. 3. Construction of shear tube anchor [23]

Since then, single bore multiple anchors are widely used worldwide in cases where conventional ground anchors do not meet requirements. In Poland, despite the fact the technology is well known – it is still used occasionally.

During the load fixed length of shear tube anchor is in compression, which is an opposite situation for conventional ground anchors [23]. In the first commercial application, in silty sand in Shrewsbury, a load of 900 kN was achieved for 6 m fixed length. A fifty percent increase in capacity compared to a conventional anchor was proved. This system, like the single bore multiple anchors, was a step forward in increasing the bearing capacity of anchors, but differences in construction were significant.

All strands of shear tube anchor were stressed at once by a single multi-strand hydraulic jack, what causes uneven strain of every strand [22]. This is the opposition to SBMA technology, where equal tendon strain should be maintained to mobilise equal bond stress at the interface of fixed length and soil.

The first commercial scale single bore multiple anchors application was in 1988 at Southampton. Anchors had multiple, separate anchor units in encapsulations in one fixed length, which were loaded individually. The five unit anchor (3.5 m each), achieved total load of 1337 kN in clayey Bracklesham Beds [24].

2.3. Construction of SBMA

Usually it is considered that the tendon bond length is equal to the fixed length of an anchor. It is true for conventional anchors, where fixed length is the grout/ground bond length, and tendon bond length is theoretically almost as long as it. In case of compressed anchors there is no conventional bond length, because load is transferred by bearing plate or other rigid compressive element.

Every SBMA anchor has at least two, individually loaded, anchor units with its own individual tendon and its own fixed length in one borehole. Fixed anchors are designed in two ways: as an intentionally separated anchor units, and as a one which is considered as a uniform grout body. It is not obligatory, but acceptable to separate fixed anchors – described in details below. One or multiple tendon bond lengths are located one behind the other along borehole axis. The result is that tendon of a proximal fixed anchor has shorter free length in opposition to tendons of distal fixed anchor which has the longest free length, which crosses proximal unit. Load is transferred from bond lengths to the grout body and then to the soil. In most cases multiple fixed lengths are designed to be in tension, so the sum of tendon bond lengths is equal to fixed length.

One fixed anchor with multiple tendon bond lengths is the most frequently used system (Fig. 4).

Every tendon has a precisely defined beginning and the end of the bond length, which transfers the load by its own grout body to the soil. In case of simultaneous loading, despite the tendon bond lengths are physically in one grout body, the uniform bond stress along the fixed length is mobilized. During the work the proximal anchor unit physically separates from the distal unit when grout body cracks between adjacent tendon bond lengths.

Separated fixed anchors system is less popular worldwide, but was used at Polish sites described in following sections (Fig. 5).

Separation is created by separators (Fig. 6) – compressible elements located between free length and fixed length of an anchor.

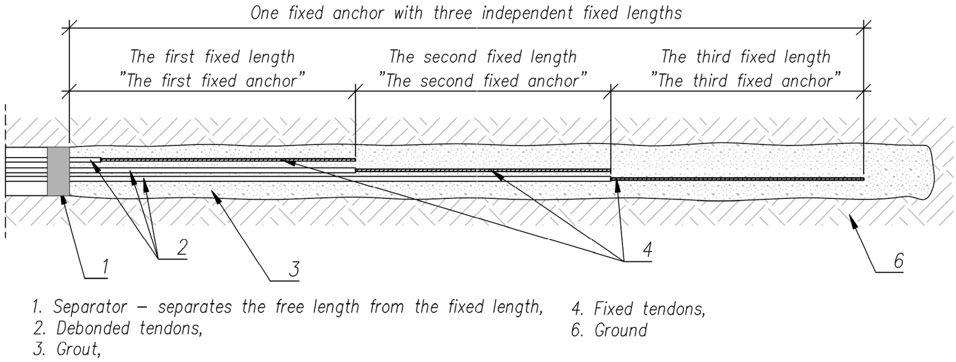

Fig. 4. Scheme of three fixed anchors considered as one uniform grout body

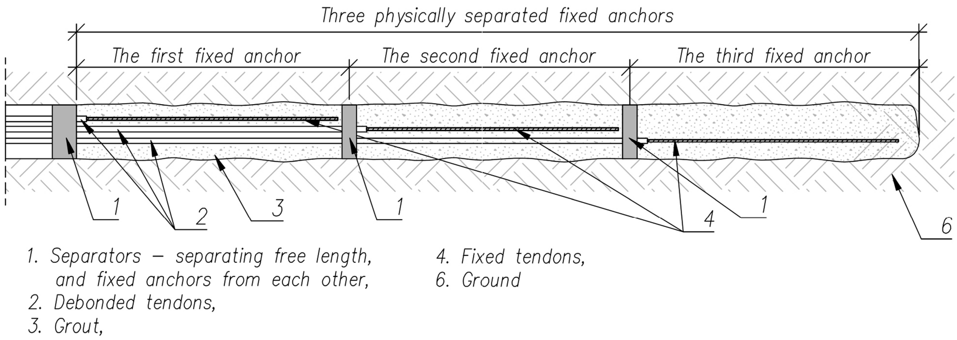

Fig. 5. Scheme of three physically separated fixed anchors in a SBMA anchor

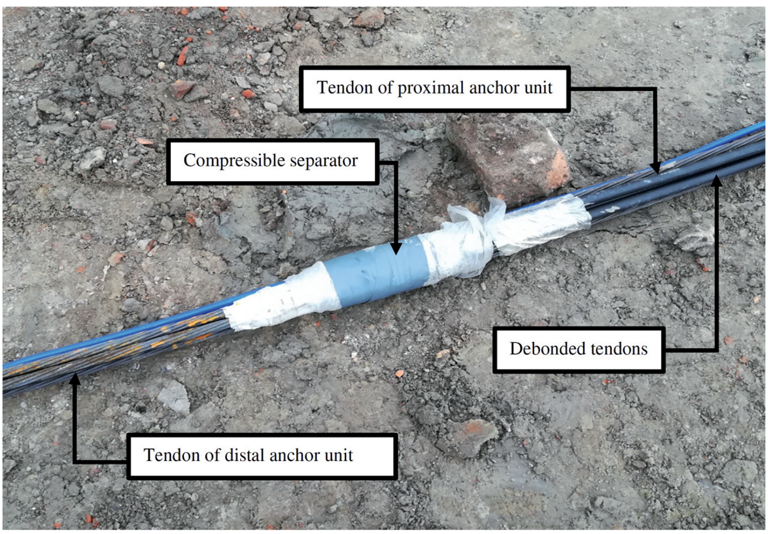

Fig. 6. Separator between two fixed anchors

Between anchor units in SBMA anchors separators create a small gap. Presented system allows small displacements and strain differences for each anchor unit. As in the first system every fixed length has its own dedicated tendon, but the difference is that on every end of an anchor unit the separator is located.

The possibility of fixed lengths small displacements along the anchor axis is required. Theoretically, the separator should physically separate fixed lengths over the entire cross section, but during tendons installation, a grout-filled void between the separator and the edge of the borehole lefts. Under the work load grout body cracks in its weakest point – at the separator.

3. Applications of the Single Bore Multiple Anchor system

There are many examples of successful application of the Single Bore Multiple Anchor technology around the world. Its creep reducing properties were proven by extended creep tests in Hodenpyl Dam in Michigan [25] and Kuntsevo Shopping Centre in Moscow [11]. Permanent SBMA anchors were part of Hunter River Remediation Project in Newcastle (Australia) and as a slope stabilisation solution in A2 motorway in Austria [11, 26].

Probably the first application of Single Bore Multiple Anchor system in Poland took place in 2003 on a site of Zlote Tarasy Shopping Centre (Fig. 7) [27, 28].

Fig. 7. Two hydraulic jacks during the suitability test of 2-unit SBMA anchor

Since that time, the SBMA system was used in Poland. Although, in terms of its range of application, it cannot be considered as a popular technology so far. The lack of specific instructions and recommendations in the literature and standards may be a reason for this situation. One of the recent examples of the technology application in Poland was the "Forest" building in Warsaw in 2020 [29]. SBMA anchors were used as a support for diaphragm walls in difficult ground conditions. Considering the forces that anchors had to transfer and the fact that in the area of anchor units were silts and clayey silts, using conventional anchors was unreasonable. Another example is one of faculties of the University of Warsaw [30], where time and costs of construction were reduced by using twice as few SBMA anchors as designed conventional anchors.

4. Anchors testing at Zlote Tarasy site

4.1. Background information

At the construction of the Zlote Tarasy shopping centre in Warsaw, as a support of diaphragm walls, conventional and SBMA anchors were designed. Due to first use of this technology in Poland, it was decided that two investigation and two suitability tests will be carried out. The main purpose of this research was to determine the effect of the prestressing order of one fixed anchor on the performance of the other, so that a single hydraulic jack and simple commonly known procedures for contractors could be used.

Investigation tests were made for anchors B1 and B2 (Fig. 7) [27], and suitability tests were made for anchors B3 and B4 (Fig. 8) [28].

Fig. 8. Measurement stand for suitability tests of B3 and B4 anchors

B1 was a conventional and reference anchor with free length of 10.3 m and fixed length of 9 meters, the remaining anchors were two-unit SBMA anchors, with fixed lengths of 4 meters each and free length of 12.0 m. All of executed anchors had a same borehole diameters of 133 mm. Every strand had a diameter of 15.5 mm (141.5 mm^2) and was made of prestressing steel with tensile strength of 1800 MPa and elastic modulus E = 195 000 MPa. B1 anchor contained 6 tendons – what gives 849 mm^2 of cross section in total. SBMA anchors B2, B3 and B4 had 3 tendons in each fixed unit what stands for 424.5 mm^2 in total for each unit. Fixed units were executed as a twice injected with injection pressure of approximately 3 MPa.

Ground conditions in the area were homogeneous for all executed anchors. Anchor borings have confirmed investigated stiff sandy clays in the area of designed fixed lengths (Fig. 9).

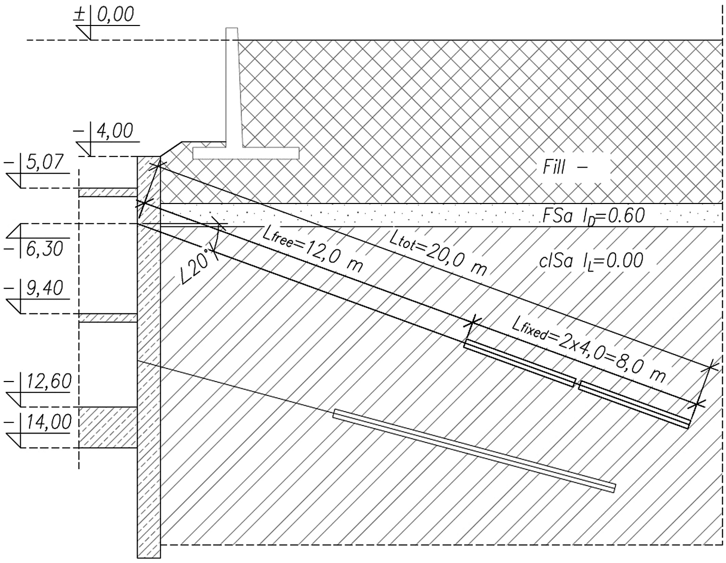

Fig. 9. Scheme and ground conditions of tested B2, B3, B4 anchors

The anchor metrics and test report were used as source material to describe the B2 anchor test. A sheet with exact force values was not available. Results in percentages were specified in the mentioned test report. The suitability tests for anchors B3 and B4 had full documentation.

4.2. B2 anchor test

The test was carried out in accordance with PN-EN 1537 (method 1) [31] and was carried out until the limit force in the tendon was reached (Table 1).

Table 1. Proof load and measured time – investigation test for an anchor B2

Load steps	Datum load [kN] ($P_a = 015R_d$)	Load (for each anchor unit) [–]/[kN]		Measurement time [min]
1	52.5	$0.50R_d$	175	5
2		$0.75R_d$	262.5	5
3		$1.00R_d$	350	30
4		$1.25R_d$	437.5	30
5		$1.50R_d$	525	60
6		$1.60R_d$	562	60
7		$1.80R_d$	630	60

Test procedure was carried out twice – the first time with separate prestress of two fixed anchors (test named B2-1), the second time with simultaneous prestress (test named B2-2). The B2-1 was carried out by prestressing the distal fixed anchor and locking it at a force of $1.00R_d$ (350 kN). After that the proximal fixed anchor was prestressed and decrease in locking force of proximal fixed anchor was measured. Due to tendon capacity, test was carried out to the force of $1,80R_d$, which is 1260 kN (for two-unit anchor).

4.3. B3 and B4 anchors tests

Next two two-unit anchors (B3 and B4) were tested in a similar way as a B2 anchor. Testing differed in order of prestressing and load steps (Table 2).

Table 2. Proof load and measured time – investigation test for anchors B3 and B4

Load steps	Datum load [kN] ($P_a = 015R_d$)	Load (for each anchor unit) [–]/[kN]		Measurement time [min]
1	52.5	$0.38\,R_d$	131	15
2		$0.60\,R_d$	210	15
3		$0.83\,R_d$	289	15
4		$1.05\,R_d$	367.5	30
5		$1.28R_d$	446	30
6		$1.50R_d$	525	180

The proximal fixed anchor was prestressed first, then it was locked, and the decrease in it's force was measured during the prestressing of distal fixed anchor. Suitability test were also carried out twice. B3-1 and B4-1 were tests of separate prestressing. B3-2 and B4-2 were test of simultaneous prestressing. The difference of load steps were due to the fact that B3 and B4 anchors were supports of the designed diaphragm wall.

4.4. Results

The report of an investigation test of B2 anchor showed that the load of the distal fixed anchor has decreased. Distal anchor unit was prestressed first and locked at the load of 350 kN. The proximal fixed anchor was prestressed as second to the load of 525 kN. Distal anchor unit load decreased by 10% (~35 kN) due to prestressing of a proximal one.

The suitability tests of B3 and B4 anchors proved that the load of the firstly prestressed fixed anchor also decrease, despite of prestressing in opposite order. The procedure of the test was to prestress proximal fixed anchor as first, and the distal one as second. The suitability test of B3 anchor showed the decrease in load by 20 kN, which stood for 6% of the lock-off load. In case of B4 anchor the load dropped 45 kN, which was 14% of its lock-off load. The detailed results are shown in Table 3. The existence of mutual influence of prestressed fixed anchors on each other was confirmed.

Table 3. Absolute and percentage decrease in lock-off load of proximal anchor unit

Load step	Load of the distal fixed anchor	Lock-off load of the proximal fixed anchor	Load decrease related to the "0" measurement		Lock-off load of the proximal fixed anchor	Load decrease related to the "0" measurement	
		B3 anchor	B3 anchor		B4 anchor	B4 anchor	
[–]	[kN]	[kN]	[kN]	[%]	[kN]	[kN]	[%]
0	53	316	0	0.00	314	0	0.00
1	131	314	2	0.63	305	9	2.87
2	210	309	7	2.22	305	9	2.87
3	289	312	4	1.27	295	19	6.05
4	368	303	13	4.11	287	27	8.60
5	446	296	20	6.33	269	45	14.33

5. Conclusions

Over the thirty years of history and development of Single Bore Multiple Anchor the technology proves its wide range of application, even in challenging engineering tasks. The construction, phenomena used in the SBMA technology and differences from conventional anchors are presented in the paper. So far two methods of execution of the fixed anchor – as one solid grout and with separate anchor units – are acceptable. Even though the SBMA technology has been used worldwide for many years, there are still no official recommendations or standards for design and execution.

The economical and engineering advantages of the Single Bore Multiple Anchor technology together with safety benefits are the reasons why it is widely used around the world. However, there are no studies on the interaction of SBMA fixed anchors with each other. Knowledge on this subject will no doubt increase the advantages of the applicability of the method. Despite many years of experience with the SBMA technology, some phenomena that probably effects on it have not been researched.

In the paper, the presented case study indicates the existence of mutual influence of prestressed fixed anchors on each other. It was demonstrated for different two-unit anchors and in opposite prestressing order. The wide range of parameters may have potential influence on this phenomenon, and its exact genesis is still unclear. Results confirm the need of further research in this area.

The research should provide a specification of more precise SBMA anchors execution and design recommendations. Simple prestressing requirements, using a single hydraulic jack, would be a significant improvement for contractors. Future design, execution and maintenance standards should consider the mutual influence of prestressed fixed anchors.

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Kotwy wielobuławowe – teoria i wnioski na podstawie badań kotew

Słowa kluczowe: kotwy gruntowe, kotwy wielobuławowe, głębokie wykopy, nośność graniczna kotew gruntowych

Streszczenie:

Wielobuławowe kotwy gruntowe są technologią dobrze znaną i wykorzystywaną głównie w zabezpieczaniu głębokich wykopów w niekorzystnych warunkach gruntowych, jako elementy utrzymujące stateczność obudowy. Główną różnicę w stosunku do konwencjonalnych kotew stanowi fakt posiadania kilku buław w jednym otworze wiertniczym. W niniejszym artykule przedstawiono cel stosowania, najważniejsze czynniki wpływające na nośność graniczną, a także krótką historię technologii. W związku z ograniczeniem zjawiska progressive debonding można uzyskiwać wyższe nośności, jednocześnie zmniejszając efekty związane z konsolidacją otaczającego kotwę gruntu. Wyjątkowe właściwości tej technologii mogą wpływać na redukcję kosztów prowadzonych robót i wzrost niezawodności i bezpieczeństwa konstrukcji. W większości przypadków kotwy wielobuławowe są sprężane za pomocą zsynchronizowanych siłowników hydraulicznych, choć jest to skomplikowane wykonawczo, aby zapewnić równomierny rozkład sił w każdej z buław. Pomimo niezaprzeczalnych korzyści płynących ze stosowania tej technologii, nigdy nie zdobyła w Polsce popularności, choć pierwsze konstrukcje tego typu wykonywano już na początku lat dwutysięcznych. Kotwy wielobuławowe stanowią mały odsetek spośród wszystkich kotew wykonywanych w naszym kraju. Powodów tego można doszukiwać się w słabo zbadanym zjawisku współpracy i wzajemnego oddziaływania na siebie oddzielnie sprężanych buław, a także związanego z tym braku szczegółowych wytycznych projektowych i wykonawczych. Celem artykułu jest przedstawienie wyników badań wstępnych i badań przydatności kotew, które odbyły się w 2003 roku na budowie centrum handlowego Złote Tarasy w Warszawie. Wyniki wskazują, że sprężenie jednej z buław powoduje spadek siły blokowania drugiej buławy niezależnie od tego, która z nich była sprężana jako pierwsza. Zmierzone

wartości wahają się pomiędzy 6% a 14%. Przeprowadzone badania sugerują, że buławy wpływają na siebie nawzajem wskutek ich oddzielnego sprężania. Przedstawione wyniki stanowią podstawę dalszych badań, związanych ze wzajemnym oddziaływaniem buław, mających na celu opracowanie wytycznych projektowych i wykonawczych wielobuławowych kotew gruntowych.

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