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LARGE-SCALE TESTING AND LONG-TERM MONITORING OF REINFORCED EARTH ABUTMENT – A CASE STUDY

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Abstract. Standard methods of controlling geotechnical structures are based on testing of individual elements (e.g., piles, anchors, barrettes) or on inventory of their displacements (for instance, current control, i.e., monitoring of retaining structures). It is only the bridgework where, due to uniqueness and importance of structures, the examinations are often run for the whole structures. The main problems are then the following: how to ensure proper repeatability of measurement accuracy (for long-term testing), how to establish optimum criteria of assessing the test results, how to use the results to make possible repair actions and how to interpret the obtained results. Based on an example of test of bridge abutment out of reinforced earth, the paper presents the method of displacement testing, basic criteria of assessing the results, measurement results during static load phase, during dynamic phase and results of long-term measurements. Large number of measurements enables for both evaluation of technical condition of the structure under testing (which was the main goal of the procedures performed) and drawing conclusions referring to the methodology of testing the structure out of reinforced earth as concerns the evaluation criteria adopted.

Keywords: bridge abutment, displacement control, load test, monitoring, reinforced earth.

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Introduction – Defects of just built structure

The abutments of the overpass under analysis were constructed using reinforced earth structure including, but not restricted to, reinforcing synthetic strips and concrete facing panels, creating vertical front walls and triangular slanted wings in both two abutments. An active system of reinforcing was used, i.e., the reinforcing strips should be slightly pre-tensioned before the soil is compacted.

When visual inspection was run directly after completing the construction and prior to putting into service, the following observations were made:

- Precast concrete facing elements did not make smooth and flat surfaces; bulging of the facade, offsets between elements, deviations from vertical, large differences in gaps between prefabricated facing elements were found; in extreme cases, the shape irregularities (deviations from design surface) exceeded 10 cm at local wall height of ca. 4.5 m (i.e., over 2% of wall height);

Figure 1. General view of the overpass

Figure 2. View of the facade elements of the abutment retaining structure

Figure 3. Selected shape defect of retaining structure surface

- The most breach of facade shape of the front retaining wall was found in upper sections of the front wall structure, and also in some areas of abutment wings;
- No deformation of straight line of prefabricated cornice elements on wing copings was visually observed;
- Visual inspection found no deformations on road pavement of approach roads;
- No atypical displacements in expansion joints were detected.

General view of the object is shown in Figures 1 and 2. Figure 3 shows a selected defect of retaining structure. A set-off between facing panels and their rotations and inclinations are visible. Prefabricates are clearly displaced each other and many of them are not in vertical plane.

The nature of visible defects indicated insufficient pre-tensioning of reinforcing strips. This way displacements of prefabricated facing elements revealed errors in constructing the reinforced earth structure. Presumptions were formulated about the reasons of these errors; however, no details could be determined as it was impossible to dismount even a single element displaced out of the distorted wall.

Essential and visually clear distortions of the shape of retaining structures resulted in decision to suspend putting the object into service. Due to the defects found, additional testing was proposed, including, but not limited to, load test of the structure. During testing, the embankment was loaded with prefabricated concrete road plates placed within the roadway at access area to the overpass; the value of load was close to that assumed in static analysis of the structure. Measurements made during testing included displacements of selected points on facing panels, displacements of columns of adjacent supports, and also vertical displacement of roadway pavement; also the mutual positions of panels were observed. Following load test, the object was approved for public traffic; however, decision was taken to run long-term geodetic monitoring of the retaining structures.

1. Experiments on reinforced earth blocks

Bridge structures out of reinforced earth can be tested in full- or reduced scale models and as real objects. Measurements in such testing are focused on horizontal displacements of facing elements and vertical displacements of top surface of reinforced soil block. In some cases, also rotations of the front walls or deformations of reinforcing elements of bulk of soil are monitored. It should be noted that when the testing for a structure is introduced purposely (during construction), a design engineer may select among a large number of possible measurement techniques. It refers to both the settlements and displacements of soil, using sensors installed inside the created embankment, and also the forces generated in structure components (soil, panels and tension members). When the object needs to be evaluated, and it was not intentionally provided with measuring instrumentation, concluding about its condition may be, in practice, made based exclusively on measurements of accessible elements. As it is necessary to ensure measurement independency, geodetic techniques should be used; hence, accessible points must be additionally visible for optical or laser instruments. Concluding based on data from such measurements is quite difficult; hence, such testing techniques are rare – they are used, in practice, just in emergency situations only.

Models constructed especially for testing needs may imitate, for instance, an abutment loaded with span weight resting on it and also with service loads. In one of research undertaking, a block of reinforced earth was prepared with dimensions of about 6×7 m in a plan view and about 5 m high. On a top horizontal surface of the block, there were prepared concrete footings that supported hydraulic cylinders, which forced the load using vertical bars penetrating through the footings and the whole block to the concrete mainstays made at the level of foundation of anchoring elements. Measurements were focused on settlement of reinforced earth block top surface and on displacements of side vertical surfaces (Wu et al., 2008). The described testing featured settlement of concrete strip footings made on the top of soil block being examined, amounting to about 16–18 cm corresponding to stresses in soil up to 800 kPa, hence, much higher than those appearing in practice. At the same time, side displacements of prefabricated facing elements were observed; in extreme cases they amounted to about 8 cm at maximum load. Also cracks of concrete prefabricates were noticed. It should be mentioned that measured deformations of reinforcement elements of earth block reached about 2% at standard stress under the concrete load bench equal to ca. 200 kPa. Contrary to the study mentioned above, the goal of the case study outlined here was to assess reinforced earth block behaviour under considerable loads while considering its real bearing capacity and deformation of the whole structure.

Another example of the testing of reinforced earth structure carried out on specially built natural scale models is given in Farrag et al. (2004). However, the tests were focused on the assessment of stresses in the soil and in the reinforcement. The next example is the monitoring of a specially constructed and equipped with measuring devices a reinforced earth block on a natural scale (height 4 m) with a non-vertical but steeply inclined front surface (Benjamim et al., 2005). In this case, the attention was focused on the displacements of the block elements and the results of the measurements were compared with the results of numerical analyses. It should be noted that in some cases, reinforced earth structures are tested in laboratory conditions, wherein models of objects on a reduced scale are under investigation (Kim et al., 2020). The results of such tests may be useful in the assessment of deformation of structures with more complex shapes.

Testing can be also made for real structures of bridge supports, as, e.g., overpass abutments (Abu-Hejleh et al., 2002). In the case under consideration, monitoring was carried out for the progress of reinforced earth block deformation during construction and service. The abutment plan view dimensions were 8×35 m approximately and height of almost 9 m. Evaluations were made for displacements of facing elements of reinforced earth both during construction of retaining structure and during loading it with concrete support and overpass span. Testing referred also to rotational displacements of facing elements and strains in reinforcement of the earth body. Horizontal displacements of facing elements, always towards outside the earth body, reached about 10 mm which was less than 0.2% of the wall height. Following putting the overpass to service, monitoring was carried out for 18 months; over 90% of displacements occurred during the first 12 month of overpass usage. It was proved that at least 50% of total displacements occurred after no more than 1 m high soil backfilling was placed above the analysed level of reinforcing strips.

In contrast to the above mentioned research undertakings, the measurements outlined below were initiated because of alarming state of the construction noticed and were carried out on distorted block out of reinforced earth. Hence, these tests were not planned prior to execution of the object. The load test and monitoring of the structure were intended, first and foremost, to assure the investor of proper safety of the whole object. As there was no access, no measuring instruments were introduced into the body of earth structure. The control points were arranged just on external surfaces of abutment and observations were made with geodetic instrumentation. Also visual inspecting took place to find possible cracks and mutual displacements of facing elements.

It is worth mentioning that reinforced soil structures, not only constituting bridge elements, are also tested with more advanced methods, such as using fibre optic sensing (Moser et al., 2016).

2. Overpass under study

The object under analysis was built in 2013 along the local road with very weak traffic in a rural area. However, during the harvest season, numerous trucks loaded with apples pass through the bridge. It is a single-span overpass operating as a simply supported beam. Basic information about the structure under study is juxtaposed in Table 1.

The overpass span does not load the retaining structure out of reinforced earth, and the embankment enclosed with retaining structure does not load the overpass supports. These both components contact each other via a transitional plate, whose one edge is based on backwall of the support, and the other edge – on the block of reinforced earth.

3. Material data

The subject of research is the abutment out of reinforced earth composed of non-cohesive soil on a non-cohesive soil basis, and – more deeply – on cohesive soils. Fundamental soil parameters are given in Table 2.

The front wall of the abutment was made out of panels of dimensions (the standard product in cruciform) of about 1.5×1.5 m (Figures 1–3). The Geostrap5 polyester strips with the following parameters were used as the reinforcing elements (Table 3).

4. Method of displacement control in course of the test

Displacement control of engineering structures is usually carried out using an external reference system. It is especially important for heavily loaded structures, in which effect on the structures themselves and on soil base causes considerable displacements, including risk of displacements of reference points. Measurements in local coordinate system provide just the possibility of measuring the relative values. Various geodetic methods are used to make measuring values independent from possible effects of subsiding trough (Mill et al., 2015). Examples of such measurements can also be found in the work of Muszyński & Rybak (2017a).

In the described case of the research, the classical measurement method supplemented with the method of laser scanning of the abutment surface was used. Displacement measurements were carried out using a Leica FlexLine TS09 total station. Height measurements were

Table 1. Basic information on the structure under study

Element	Data
Span	Composite, steel-and-concrete structure
Main girders	Steel beams (plate girders)
Deck	Reinforced concrete slab
Theoretical span length	36 m
Span support	3 columns, transverse beam and backwall
Wings and front walls of abutments	Reinforced earth structure Facade panels out of concrete prefabricated element
Reinforcement of soil block	Polyester strips

Table 2. Geotechnical parameters of soil

Soil name	Bulk density, γ kN/m^3	Internal friction angle, ø °	Cohesion, c kPa	Deformation modulus, *E* MPa	Deformation modulus, *M* MPa
Reinforced earth: medium sand + gravels	19.0	Taken results of 35–45	0	110*	150*
Basis: fine/silty sands, thickness up to 3.6 m, ID = 0.52	18.5	32–35	0	90**	110**
Soil below 3.6 m deep: sandy clays, loamy sands, thickness up to 10 m, with fine sand intrusions, IL = 0.35–0.66; more deeply: fine sands, ID = 0.52–0.78	19.0	26.5	12	27***	37***

Note: * Based on CPT probe tests, ** Based on correlation tables, *** Based on criteria included in design analysis

Table 3. Basic information on the polyester stripes

Parameter	Data
Thickness	4 mm
Width	50 mm
Length from wall face	Up to 8 m
Tensile strength (short-term)	50 kN
Tensile strength (long-term)	7.14 kN
Tensile modulus	2.5 GPa (Abdelouhab et al., 2010)

carried out with the Leica NA3000 electronic level. As complementary activities, the surface of the abutment was scanned with the Faro Focus S70 scanner. Measurements of horizontal displacements were made based on three points of the measurement network, and the levelling was carried out in relation to the base point and control point, both located on the other side of the obstacle, i.e., the railway line. All reference points were located at a considerable distance from the abutment under study, i.e., over 20 m. These points are not marked in the drawings presented below. The coordinates of the test bench (i.e., positioning of the measuring instrument) were achieved with an accuracy better than 1 mm.

Geodetic measurements, which were the main element of testing, were made assuming the following conditions:

- Measurement points were arranged on facade panels and column supports and on the roadway pavement;
- Rangefinder shields were placed in measurement points everywhere, except for pavement of roadway;
- The requirements were that the measurements should provide result accuracy up to ±0.3 mm on a horizontal plane and ±0.2 mm on a vertical plane.

It was found that average errors for measurements using rangefinder shields on facade panels were:

- Indentation error up to 1 mm;
- Aiming error up to 1.5 mm.

For multiple aiming, this error decreased to <1 mm. It can be assumed that the resultant average error may be around 1 mm and is comparable with the measured displacement. However, it was concluded that the accuracy was sufficient. Measurements with accuracy one order of magnitude better, i.e., up to 0.1 mm is not justified when considering the size of the object and inevitable effect of such factors as temperature variations of structure components, sunlight, effect of road traffic, etc.

It should be remembered that the investigated abutment was not originally equipped with any measuring devices, as the need for monitoring was not expected during its construction.

After making the decision to start research on the deforming abutment, the following procedure was adopted before the bridge was put into service:

- Establishing control points on the facade panels and on the road pavement (rangefinder shields were glued on the outer surface of the facade panels, and metal elements in the shape of a thick nail were inserted in the roadway pavement, the location of the measurement points S1–S18 & N1–N6 is shown in Figures 4, 5, 6);
- Taking the measurements under a test load, which lasted 17 days;

- Taking measurements every six months, during the standard operation of the bridge;
- Making a decision to terminate the research after finding a decrease in the rate of growth of displacements.

A decision was made to use geodetic methods when conducting monitoring due to the availability of good measuring equipment with professional staff and due to the lack of the need to install costly measuring devices on the site and leave them for a few years.

A number of other issues related to geotechnical monitoring are identified in the works (Muszyński & Rybak, 2017b; Drusa & Vlček, 2016; Gorska et al., 2013; Sobala & Rybak, 2017).

5. Testing of reinforced earth abutment

Engineering facilities are often of individual nature; hence, it is often necessary to set individual criteria for evaluating the structures. Load test is one of the tools, which help take decision on commissioning a bridge structure. Most often it refers to spans and supports, and perhaps occasionally to embankments. It seems quite plausible to suggest that such testing is unique. One reason of that is the fact that the earth structure is, to a large extent, loaded with its own weight, which is successively applied already during construction of embankment. Hence, test load takes place in some ways involuntarily. The other reason is that trust to massive earth structures is usually so high that large problems only (like visible settlement, landslips, earth flows, etc.) could prompt interested persons to undertake control tests. In the case outlined, the reason was visible deformation of the front surfaces of the structure.

5.1. Evaluation criteria for short- and long-term behaviour

An indispensable step before starting the research was to adopt methods of evaluating the results. The criteria for assessment of testing results were developed on the basis of data included in the test load procedure (Hildebrand & Rybak, 2016) (see Table 4). The test load in question is also described in the work by Hildebrand & Rybak (2017). The measurement results are commented to some extent and evaluated in Table 4. When analysing Table 4, see Figures 4–6.

The threshold values appearing in some of the numerical criteria listed in Table 4 are justified by various premises. Total horizontal displacement of 10 mm was limited due to the possibility of accommodating the displacements within the clearances between the facing panels. The permissible total vertical displacement (ΔH)

Table 4. Criteria and evaluation of load test results

Pos.	Criterion	Value	Evaluation
1.	Measurement points S1–S18; total horizontal displacement under static load	≤ 10 mm	Correct status
		> 10 mm	Incorrect status
	Assessment of results		
	Total horizontal displacements of facing panels were different and amounted from 0 to 2.6 mm. The displacement criterion was met as: 2.6 mm < 10 mm		
2.	Measurement points N1–N6; total vertical displacement under static load	≤ 3 mm	Correct status
		> 3 mm	Incorrect status
	Assessment of results		
	Total vertical displacements for the measuring points N1–N6 were different, from 2.7 mm to 3.2 mm. The average displacement was 2.9 mm. The settlement criterion was met		
3.	Measurement points N1–N6; the quotient of permanent and total vertical displacements – after static load is removed	≤ 70 %	Correct status
		> 70 %	Incorrect status
	Assessment of results		
	The average permanent vertical displacement for points N1–N6 as measured after three days from removing the load was 2.4 mm. The average total vertical displacement as measured directly before load removal was 2.9 mm. Hence, the quotient is (2.4/2.9) × 100 = 82%. The quotient is higher than that declared for the criterion: 82% > 70%. However, the following should be considered: – soil destressing proceeds very slowly; considering that over time the soil destressing will be continued, the results achieved were accepted; – during dynamic tests, the truck drove over some benchmarks in the roadway pavement; thus, some results were slightly disturbed		
4.	Damage of edges and corners of panels resulted from test load	None	Correct status
		Occurring	Incorrect status
	Assessment of results		
	No damage was found in facing panels caused by test load		
5.	Mutual position alteration of facing panels due to test load effects	Admissible, provided no backfill, geotextile, etc. is coming out	
	Assessment of results		
	According to visual inspection of control gypsum fillings, no mutual displacements were found for the facing panels		
6.	Additional horizontal displacements after completing the dynamic loads	≤ 1 mm	Correct status
		> 1 mm	Incorrect status
	Assessment of results		
	No meaningful displacements were found after completing the dynamic loads		
7.	Increase of displacements over time	Stabilization	Correct status
		Grow of displacements	Incorrect status
	Assessment of results		
	Assessment of displacement stability was grounded on settlement diagrams in time domain. It was found for all benchmarks that increase of settlements was stopped after 4 to 10 days from placement of the load plates. Thus, it was stated that the displacements were stabilized		

of 3 mm was estimated assuming: homogeneous stress distribution in a reinforced earth block, average value of the elastic modulus $E = 60\ 000$ kPa, embankment height $H = 10$ m and the load (stress) value $\sigma = 20$ kPa. Then the value of settlements is approximately $\Delta H = \sigma H/E = 20 \times 10/60\ 000 = 0.003$ m. The value of E was assumed appropriate for the sands from which the structure was made. This value is lower than that given in Table 2 (110 000 kPa), which is the result of local tests with the CPT probe. However, a fairly conservative value (60 000 kPa) was adopted, based on own experience in the assessment of entire structures made of this type of soil. The permissible value of the quotient of permanent and total vertical displacements equal to 70% was adopted based on the author's own experience.

5.2. Static and dynamic test load

Reinforced concrete road plates stacked to total thickness of about 1.1 m (7 layers of plates) were used as a test load. They were laid directly on the bituminous road pavement. The plates were placed over almost full roadway width, i.e., about 6 m, and along a length of ca. 9 m. In total, 84 plates were used of total weight 135 Mg (tons). The surface area loaded was $9 \times 6 = 54$ m^2. The surface load was ca. 25 kN/m^2, which was 0.93 of the design load equal to 27 kN/m^2. The road plates were placed in two stages.

The plates were not placed over the whole transition plate, so as the load was transferred rather to embankment earth than to the support via the transition plate. Load scheme and pressure distribution on retaining structure are shown in Figures 4 and 5. When determining the load position and pressure distribution, the internal friction angle of soil built into the reinforced structure was assumed as $\phi = 40°$.

Prior to starting with placing the road plates, control gypsum fillings were placed in selected points of the front wall of the reinforced earth structure in gaps between prefabricated facing elements. The test load started on 17 May 2016. Control measurements and inspections of gypsum seals (after the full load was applied) were made on 17, 18, 21, 24, 27 May and on 3 June 2016. Load was removed on 3 June 2016. Following removal of loading plates and after completing geodetic measurements and inspection of gypsum seals, decision was taken to make dynamic loading tests. They were performed on 3 June 2016. Control survey (geodetic measurements) following terminating the test load was carried out on 3 and 6 June 2016.

Measurements of horizontal and vertical displacements of control points took place before, during and immediately after placing the load and came along through successive days. The charts of settlements of selected three benchmarks N1, N2 and N5 covering first 24 hours of test, are presented in Figure 7. As it can be seen from the course of the curves, the placing of the concrete road plates, which became the test load, took about 3 hours, from 1 PM to 4 PM. The load was left on the structure for 17 days. The charts of settlement, covering 20 days of experiment, again of benchmarks N1, N2, N5 are presented in Figure 8. The relaxation of the soil after the removal of the load is clearly visible in all three curves, which are representative.

The horizontal displacements of control points S1–S18 during test load were small, i.e., up to 2.6 mm outward, the charts presenting them are not reported here. However, during later phase of experiment more substantial and more unexpected displacements were observed (see next section).

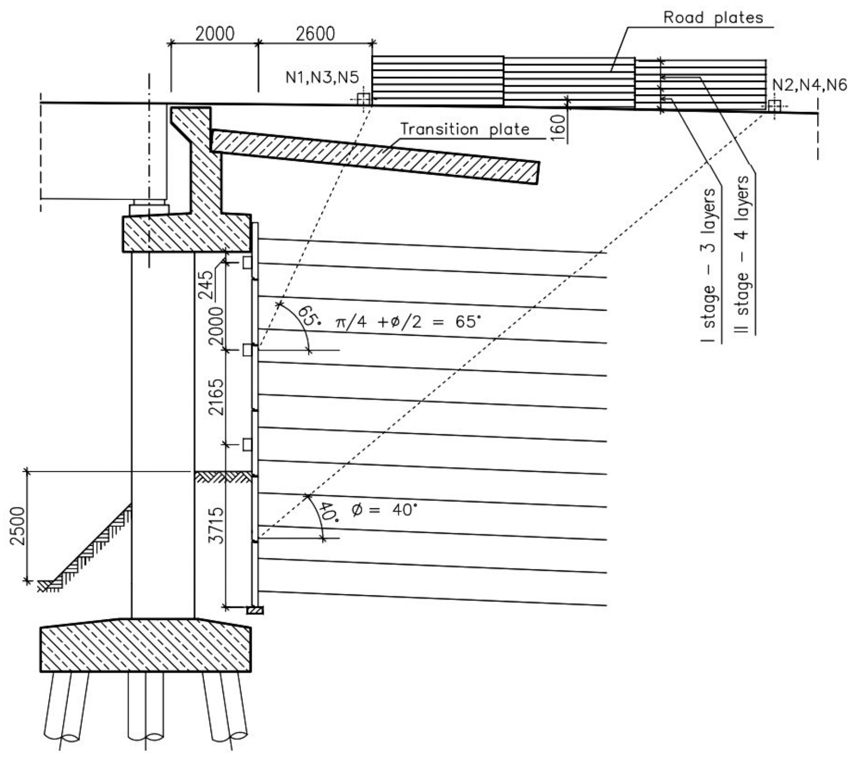

Figure 4. Arrangement of loading road plates – longitudinal view, scheme of load transfer to reinforced earth structure

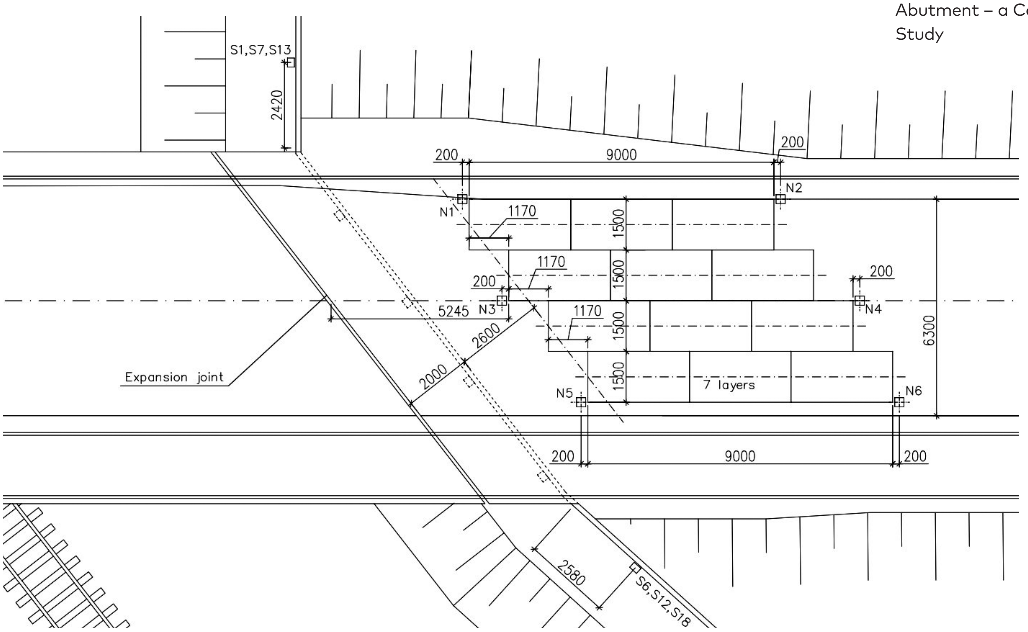

Figure 5. Arrangement of load plates – plan view

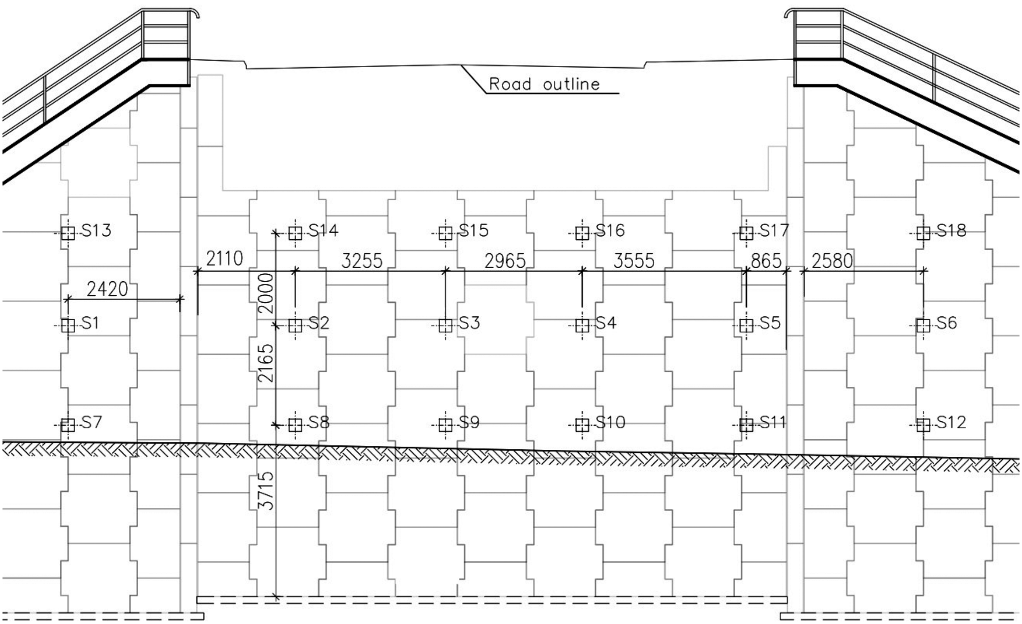

Figure 6. Arrangement of control points on front wall and wings of reinforced earth abutment

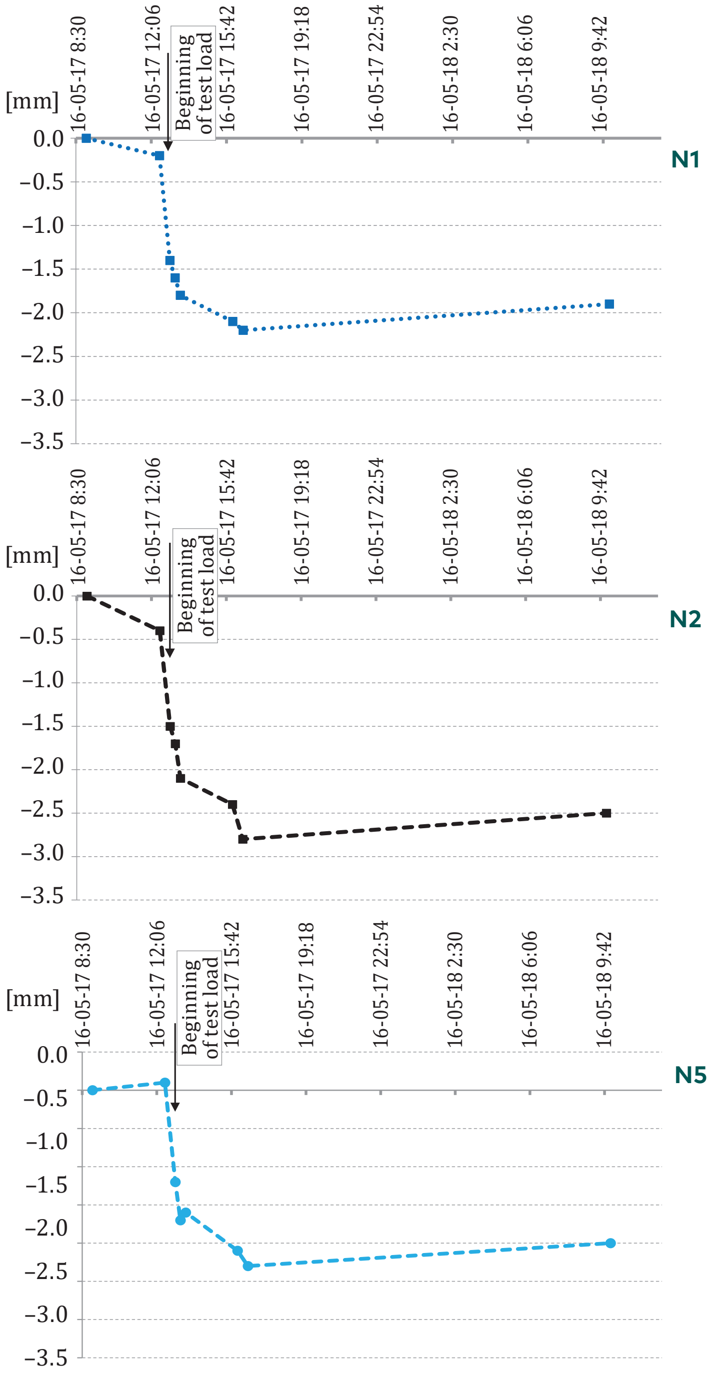

Figure 7. Vertical displacements (in mm) of control benchmarks N1, N2, N5 within 24 hours from starting test load

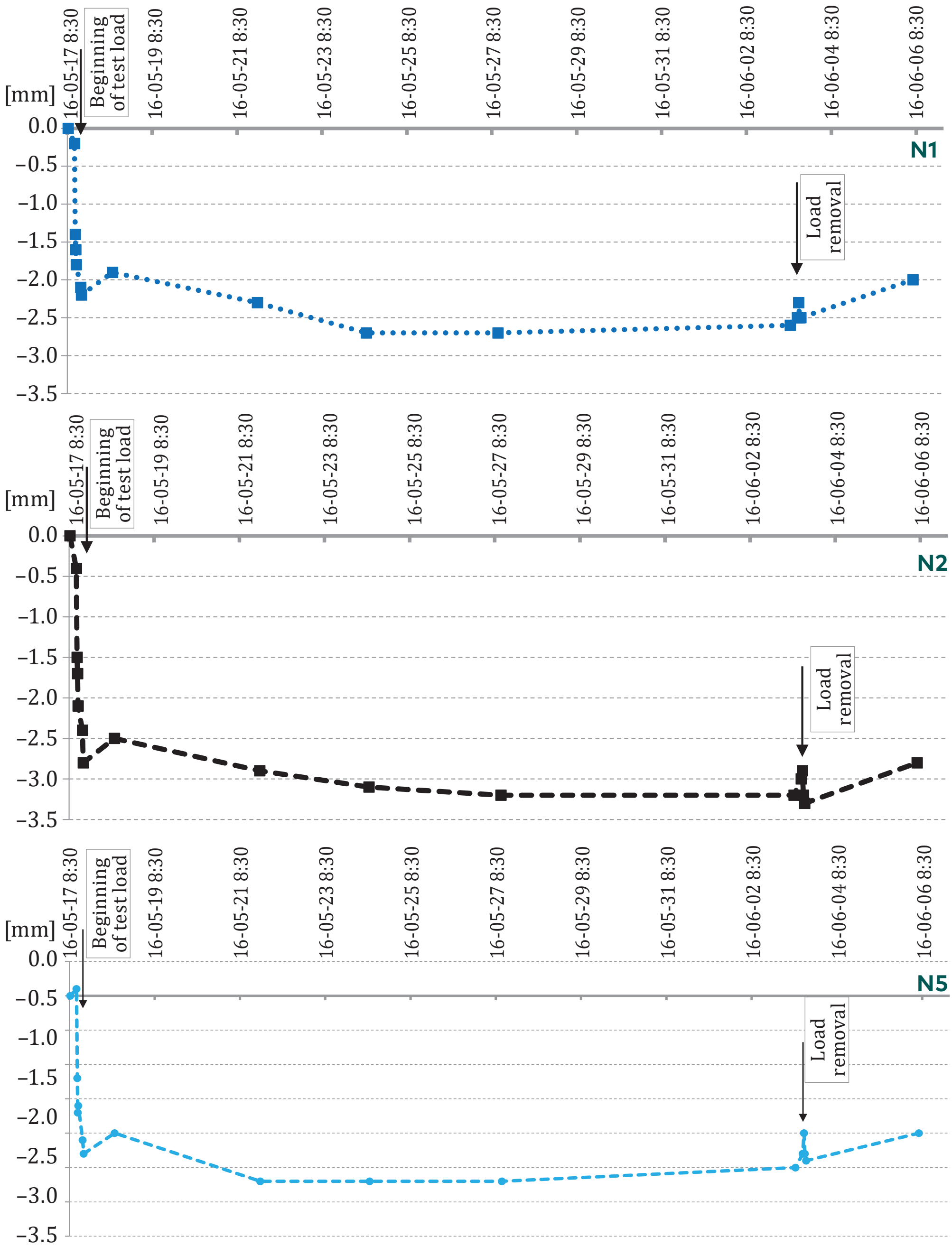

Figure 8. Vertical displacements (in mm) of control benchmarks N1, N2, N5 within 20 days from starting test load

During and after static test, the following was found:
- The structure under testing settled as expected, the settlements stabilized after around 4–10 days; on this ground, the assessment was made that the structure had some reserves of bearing capacity;
- The structure under testing did not show any alarming deformations in horizontal direction or any damage resulting from the actions undertaken.

Dynamic loading was derived from passing of a truck of total weight ca. 420 kN. The control measurements after ridings showed no essential displacements. Proper behaviour was ascertained both for static and dynamic loads. When the testing was completed, the bridge was put to service; however, a need to run continuous monitoring was suggested. The bridge was actually open for public traffic on 5 June 2017.

5.3. Long-term monitoring results

When load tests were completed, decision was taken to run long-term observations for the structure. Measurements were carried out consistently, from summer 2016 to autumn 2019 (and also later, which is not reported in this paper). It was decided, to use the same network of control points and reference points, as those, which were used during test load. It was a convenient solution, but not entirely beneficial to the results obtained, because some control points were placed in the road surface in such a way that, unfortunately, they were undoubtedly run over by trucks after opening the overpass for public traffic. It was found that benchmarks N1 and N5 were the least likely to be hit by cars and the results obtained from these points were the most reliable. The results obtained from benchmarks N3 and N4 are the least reliable. It should be mentioned that points N1 and N5 are located in such a way that the road curbs and the curb sewage partially protect these places, so truck wheels appear the least frequently near these points. On the contrary, points N3 and N4 are located in the middle of the road, where the wheels of trucks load more intensively. It is worth noting that points N1, N3, N5 located above the transition plate do not show all smaller settlements than points N2, N4, N6, which are outside the transition plate. Thus, probably the greater part of the measured vertical displacements of benchmarks results from their loading and pressing by the wheels of trucks. The results obtained from all benchmark are presented in Figure 9.

Considering the results obtained from the most reliable benchmarks N1 and N5, it can be seen that after opening the bridge for traffic, there were vertical displacements of no more than 2 mm (referring to the day the facility was opened for traffic), while the N5 benchmark did not show significant displacements. It should be borne in mind that benchmarks embedded in the road pavement could be subjected to various unexpected influences, including thermal and other unpredictable influences. It should be emphasized that the decision to place benchmarks in the road surface (and not in another place, less exposed to disturbing factors) was made when the decision on the long-term monitoring of this structure was not expected. Currently, i.e., in 2019–2020, the control of the settlement of the structure in question is carried out using other control points.

Assuming, however, that the settlements of the entire structure from the beginning of the tests were not greater than about 4 mm (see Figure 9 – N1 and N5 curves), it should be assessed that they were relatively small. Relative settlements reached 0.004 m / 10 m = 0.0004 (0.04%), where 10 m is a total height of embankment.

It is worth noting that from the removing of test load (3.06.2016) to the opening the bridge for public use (5 June 2017), very slow but consistent displacements of the N1–N6 benchmarks upwards progressed, which proved that the soil structure was slowly relaxing after the load had been removed, (see Figure 9).

In order to increase the credibility of the assessment of the technical condition and the results of monitoring of the structure under study, the long-term analysis of the total horizontal displacements of the facing panels in the direction perpendicular to the front surfaces of the reinforced earth structure was carried out. The rangefinder shields at

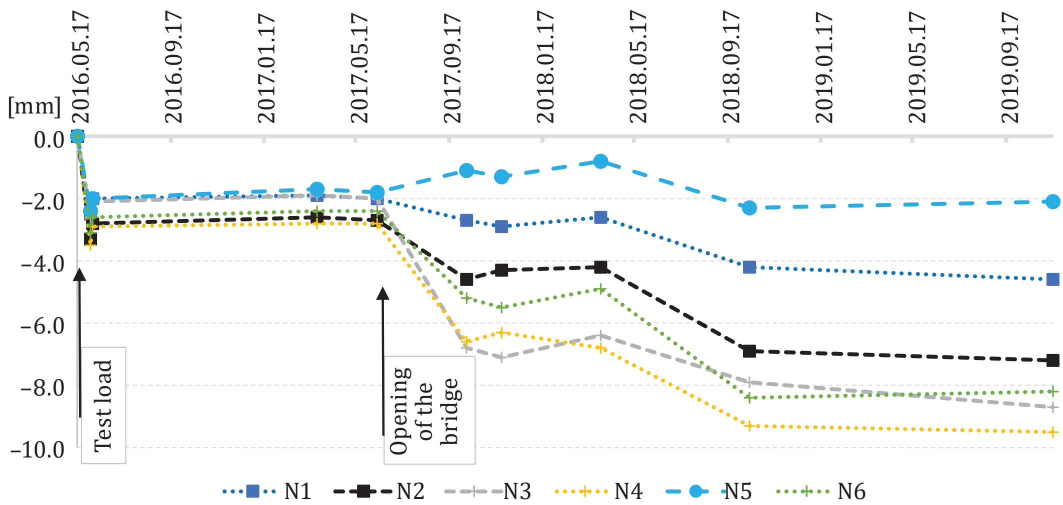

Figure 9. Vertical displacements (in mm) of control benchmarks N1–N6 within 3.5 years from starting test load

points S1–S18 were used (see Figure 6). The results obtained from the S1, S2, S4, S7 and S8 control points are not reported in this paper due to the fact that they were destroyed as act of vandalism committed. It should be mentioned that during the test load and immediately after, only slight horizontal displacements, i.e., up to 2.6 mm, were found (see Table 4). The results of long-term measurements of horizontal displacements of the control points on the facing panels are shown in Figures 10–12. It should be noted that Figure 10 shows the results of measurements of the control points located in the middle of the height of the frontal surface and the abutment wings. Figure 11 illustrates the results for the points lying in the lower part of these surfaces, and Figure 12 shows the results for the points lying in the upper part of the structure.

The term “horizontal displacement” shall be understood as a change of control point position perpendicular to the plane of facing prefabricate with respect to the zero measurement taken on 17 May 2016, i.e., prior to starting with test loading the structure. The sign (–) means that the outwards displacements were found.

It is visible that the majority of control points revealed the horizontal displacements no greater than approximately 4 mm (outward the block of reinforced earth). For only one control point (S13) the displacement of about 7.6 mm was found, again outward. However, still it was less than 10 mm assumed as acceptable horizontal displacement (see Table 4)

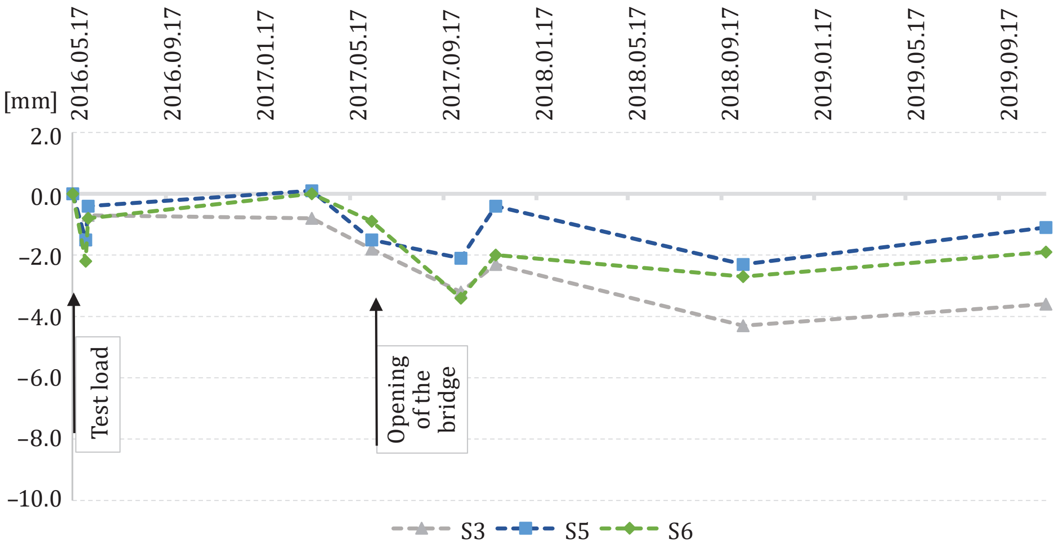

Figure 10. Horizontal displacements (in mm) of control points S3, S5, S6 within 3.5 years from starting test load

during short-time test load. It should be underlined that control points are not located in the mid-point of each facing panel. Thus, if the panel rotates the one corner can be moved outward, while the opposite one can be moved inward, which is possible if the soil is not compacted properly or some soil grains may have suffered from suffocation. It should be recalled that numerous panels have rotated, which is clearly visible in Figure 3. The observed decrease in horizontal deformations in

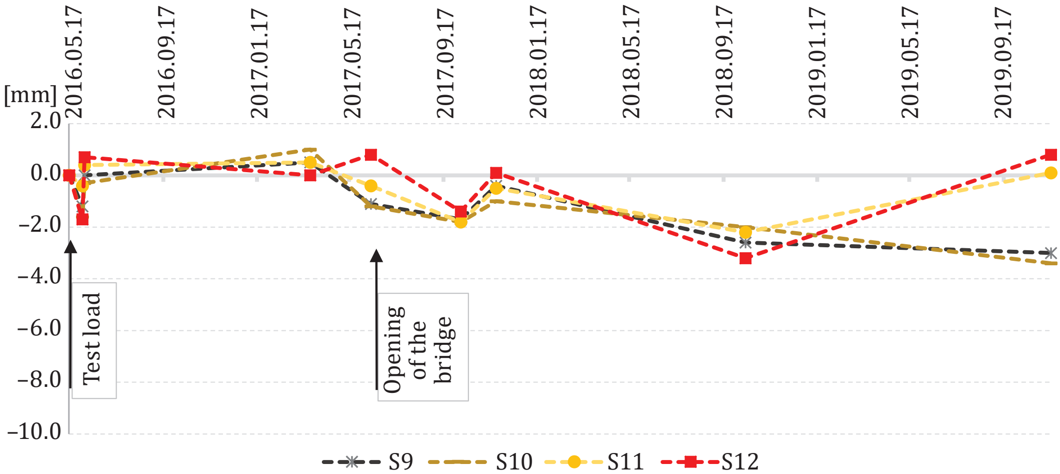

Figure 11. Horizontal displacements (in mm) of control points S9, S10, S11, S12 within 3.5 years from starting test load

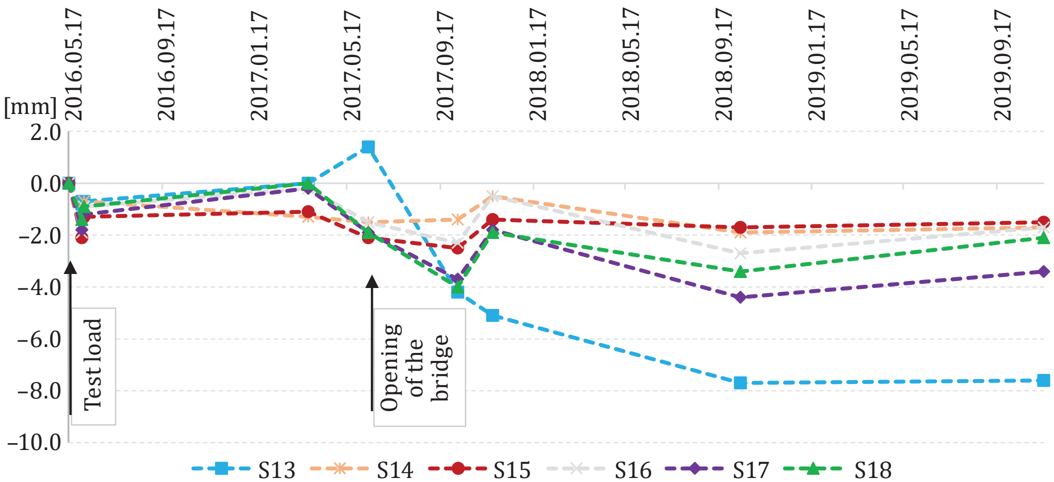

Figure 12. Horizontal displacements (in mm) of control points S13, S14, S15, S16, S17, S18 within 3.5 years from starting test load

winter 2017 is probably a delayed effect of removing the test load in June 2016 and the slowly following soil relaxation.

The value of displacements amounts to less than 0.1% of the wall height, while the deviations from the planned plane of the walls found immediately after the completion of construction were about 10 cm, which was more than 2% of the front wall free height (ca. 4.5 m). It is worth noting that the horizontal displacements of the control points were not as susceptible to the effect of the test load as to the dynamic effects occurring after opening the viaduct to public traffic.

Final remarks and conclusions

The adopted strategy of proceeding with regard to the viaduct in question turned out to be correct. The structural safety of the viaduct made with undoubted deficiencies was verified on the basis of the test load results, and at a later stage – on the basis of the results of monitoring measurements. The applied classical method of geodetic measurements proved to be sufficient in the presented task, and at the same time it was relatively cheap. The displacements of the control points located on the structure were small, i.e., did not exceed a few millimetres. In some cases, a large proportion of the measured displacements of relatively small values may have been induced by undesirable effects such as temperature changes, the influence of the sun radiation on the structure, etc.

During the observation of the object before it was put into operation, the effect of relaxing of the soil block after removing the test load, both in terms of vertical and horizontal displacements, was observed. Later displacements were interpreted as the effect of natural settlement processes and the adaptation of the soil structure to the load condition.

The deformations of the entire tested soil block under real operational loads are small when compared to the displacements recorded under experimental conditions, at very high loads, presented in the paper (Wu et al., 2008). The tested structure described here behaved in a manner similar to the behaviour of the structure tested by the authors of the work (Abu-Hejleh et al., 2002). The horizontal displacements obtained by them (0.2% of the wall height) were relatively greater than the displacements found during the tests presented in this paper (approx. 0.1% of the wall height).

The conducted tests of reinforced earth structure allow concluding that despite the irregularities in shape, the entire reinforced soil block behaves properly. Despite these flaws in shape, which are a manufacturing error, the abutment – just like the entire facility – can be exploited.

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