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INNOVATIVE COMPACTION TECHNOLOGIES FOR REHABILITATION OF FLOOD PROTECTION DIKES

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ABSTRACT: The innovative dynamic compaction technologies like variocontrol rollers with polygonal drum and the Rapid Impact Compactor (RIC) enable an optimization of earth works. The polygonal drum is an advancement of conventional smooth round or padfoot drum and offers considerable advantages for the near surface compaction. The drum consists of octagonal elements which are in an axially staggered arrangement to each other. During the compaction the structured drum shape provides a constantly-changing direction of forces and results into a kneading effect of soil. This action leads to a deeper and homogenous compaction effect. The Rapid Impact Compactor is a dynamic compaction machine based on the technology of the pile-driving hammer. By using this technique the ground or respectively the fill materials are compacted and improved by a high frequency of controlled impacts of a falling weight from a defined height onto a plate. For efficient energy transfer into the deeper ground the plate remains in contact with the ground during the compaction process. The successful application of both innovative compaction technologies for remediation of existing flood protection dikes is presented in this paper.

1. Introduction

In the past decades the catastrophic floods demonstrated the bad conditions of numerous flood protection dikes in many regions in Austria and its neighbouring countries. The numerous damages showed the necessity to achieve a high stability and functional capability not only for dikes but especially for temporary stressed flood embankments. In most parts their lacking current state is given primarily through the historical development of the flood control measures. The construction of such earth fill flood protection structures was carried out by using very simple equipment. It means, that especially the older dikes and flood embankments represent a high risk potential concerning a failure during the next flood event. They were often built as a fill embankment with an impervious core but mostly from a homogenous material of loose packing. The fill material was usually taken from the adjacent surrounding area (floodplain) and in many cases it consists of a wide range of soils. In this case, the “homogenous” embankments have partly heterogeneous zones and strongly varying permeability. Due to a bad compaction of the earth fill material in combination with high permeability floods of low intensity can already cause a softening and/or a loosening of the fill material. Finally, in dependence on the stress duration a failure of a flood protection embankment can occur. Based on this knowledge the aim of rehabilitation of dikes should be an embankment built from a good compacted fill material with low permeability. For the reason of an optimization of the refurbishment process grows the need for new compaction techniques.

Those innovative compaction techniques, like self-controlled vibrating rollers with polygonal drum for near surface compaction and rapid impact compactors for middle deep compaction for the remedial works on dikes were used for the first time worldwide in Austria. These compaction methods were primarily applied on dikes at the Danube river, the river March (Morava) and at the river Kamp.

Fig. 1: Dike failure at the river Aist in the year 2002.

Fig. 2: Failure of a flood protection dike during the flood in 2006 at the river March.

2. Remedial work concepts

The main goal of the rehabilitation of dikes or flood embankments is to maintain or to repair/refurbish the stability of the structure and in some cases to raise the origin crest level for adjustment on the defined protection level. These works should be focused also on the hydrodynamic stability of the embankment. Except a good working sealing system also filter and drainage system have to be considered.

The near surface and middle deep compaction technologies play an important role with the rehabilitation of dikes. Due to a decrease of the pore ratio of the fill material the permeability decreases significantly and the shear strength and also the embankment stability increase. Multiple compactions tests and several research works showed that an optimization of the remedial works can be successfully reached through the adaptation of the compaction techniques to the on-site conditions. The following case-studies show the technical and economical advantages by using these innovative compaction methods.

3. Rollers with polygonal drum

The near surface compaction is usually performed statically or dynamically by using vibrating, oscillating rollers or rollers with directed oscillation. Since several years also so-called self-controlled (“intelligent”) rollers (VARIOMATIC, ACE) have been used. Nowadays, especially the dynamic rollers are applied for earth works. This compaction technology allows an improved compaction due to an interaction between the dynamic forces and the static load from the dead weight of the drum. Additionally to the machinery parameters of the roller also the soil mechanical behaviour plays a very important role for compaction results. Especially for the compaction of fine grained, cohesive soils which are mainly used as a fill material for dikes the dynamic roller compaction is limited to specific soil parameters. It means that the vibrations/oscillations of the drum induce at higher water content of cohesive soils an excess of pore water pressure. They cannot relieve because of the low permeability of the soil and causes a change of consistency and a degradation of compaction values respectively. The deterioration effect can be partly reduced through the adaptation of the drum form to the compaction behaviour of fine grained soils. This innovative compaction technology, using vibrating rollers with polygonal drum, was applied for compaction optimization during the remedial works of the flood embankments at the river March.

Fig. 3: Variocontrol roller with polygonal drum.


Fig. 4: Vibrating roller with conventional smooth drum.

The polygonal drum (see Fig. 3) represents an advancement of the conventional smooth and padfoot drum respectively by means of the adaptation of the drum shape (see Fig. 4). The drum consists of three octagonal elements which are axially positioned next to each other and which are in a staggered arrangement. Rings are welded on both outer drum edges for better steering control as well as transportation on hard grounds. During the compaction the polygonal shape induces constantly-changing forces between the planar segments and the wedges of the octagonal element. When the planar segment rests on the ground only normal forces but no shear forces can be transmitted and the compaction of the soil layer is achieved. At the same time shear forces are induced through the penetration of the wedges of the adjacent elements into the ground and cause a forward movement. Furthermore, the drum wedges have a considerable influence on the positive compaction effect of the polygonal drum. At the moment of the contact of the wedge with the ground a stress peak is generated in the contact line between the drum and the compacted soil layer. The following penetration of the wedge into the ground produces splitting tensile forces which cause a lateral shift of the soil particles. Before the plate(s) (planar segments) impact again the ground, the laterally shifted soil particles can relax in direction around the wedge(s). In the moment when the adjacent plates rest on the ground stresses are distributed. The splitting tensile forces invoke in the following shear forces which are important especially for the compaction of fine grained cohesive soils.

A complete quality assessment of the compaction and documentation after each roller pass is provided by the roller-integrated continuous compaction control (CCC). This method registers the interaction between the drum and the ground and is a standard of the most vibrating rollers. Additionally to the CCC method also punctual investigation techniques can be applied: dynamic or static load plate tests, method for density determination in combination with laboratory testing and dynamic probing light (DPL), medium (DPM) or heavy (DPH), and furthermore cone penetration test (CPT).

4. Rapid Impact Compactor (RIC)

The Rapid Impact Compactor (RIC) is an innovative dynamic compaction device based on the piling hammer technology used to increase the bearing capacity of soils through controlled impacts. The general idea of this method is to drop a falling weight from a relatively low height onto a special foot assembly at a fast rate whereas the foot remains in contact with the ground at all times. At present in the Central European area there are some devices, which aim at closing the gap between the surface compaction methods (e.g. roller compaction) and the deep compaction methods (e.g. deep dynamic compaction/replacement) and permitting a middle-deep improvement of the ground.

The RIC consists mainly of three impact components: the impact foot, the driving cap, and the hammer with the falling weight. The impact foot made of steel has a diameter of 1.5 m. It remains in contact with the ground all the time. The driving cap connected to the foot allows articulation. Impact foot, driving cap, and falling weight are connected to the so-called hammer rig (see Fig. 5). Falling weights of mass 5000, 7000, 9000 or 12000 kg are dropped from a falling height up to 1.2 m at a rate 40 to 60 repetitions per minute.

Fig. 5. Rapid Impact Compactor (left), impact foot with driving cap (center top), points of compaction (center bottom) and process of compaction (right).

Data monitoring during the compaction process and the online display in the operator's cab enables a control of compaction, an economic application of the compaction tool and a work integrated quality control. The stop code is defined by the total impact depth of the impact foot, the number of blows and the final settlement of the impact foot after a blow.

The RIC allows middle deep compaction up to a depth from 4 to 7 m in an efficient an economic way. The comparison to other dynamic compaction techniques with respect to the depth effect shows that the RIC is an ideal amendment between surface near compaction technologies (static and dynamic rollers) and deep compaction techniques (deep vibro compaction, vibroflotation and deep vibro replacement, heavy tamping).

Gravels, sands, silts, industrial byproducts, tailings material and landfills can be successfully compacted by the RIC. Thus, the rapid impact compaction can be used to increase the bearing capacity of foundations, for the improvement of ground bedding conditions for slabs, for the reduction of the liquefaction potential of soils, for the stabilization of waste materials and for the remediation of existing embankments and flood protective embankments. The last application possibility is presented in chapter 5 using the case history of a test dike that has been improved with the Rapid Impact Compactor.

5. Case Studies

5.1 Remedial works at the flood protection dike at the river March (section Hohenau an der March) using rollers with polygonal drum

The flood protection dikes at the river March were exposed to high stresses during the floods in the years 2002 und 2006. In many parts softening and loosening of the fill material from the embankment body occurred that required extensive rehabilitation works along the entire river bank on the Austrian side of the river March. For this reason a refurbishment concept was worked out; it was intended to remove the existing embankment body including 0.5 m thick soil layer underneath the natural terrain level. Finally, after the compaction of the “removed planum”, the existing fill material had to be compacted in layers and the flood embankment body had to be rebuilt to the crest level which was bilaterally assessed by the Austrian and Slovakian authorities.

A time lag of the earth works in the section “Hohenau an der March” raised due to a longer rain period which induced a flood event. For this reason an optimized compaction concept was specified. According to this concept a layer of about 1.0 m of the existing embankment including the 0.5 m soil layer underneath the embankment base had not to be removed. Afterwards, this remaining part of the existing embankment body was compacted by using an innovative technology of variocontrol rollers with polygonal drum. Because of the optimized compaction effect and greater compaction depth it was expected that the compaction will be achieved also underneath the virtual formation level of excavation assessed in the original concept.

The suitability of the optimized compaction concept was proved on a test field, where the compaction effect of both types of drums (both compaction concepts) was compared to each other. The compaction control was performed by roller-integrated CCC-System, light dynamic probing tests and dynamic load plate tests.

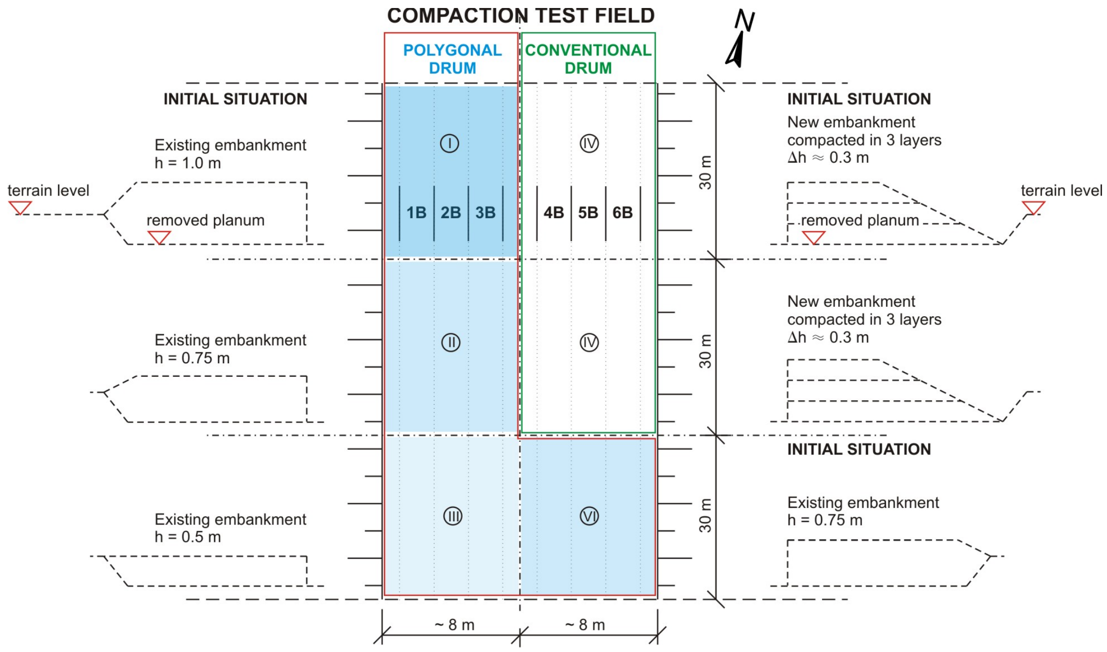

Fig. 6: Compaction test field.

The fill material of the existing flood embankment in the area of the test field consisted predominantly of sandy silts to silty sands and partially only of sands of narrow grain size distribution. The natural soil layer underneath the embankment base had a similar range of soils, where sandy silts dominated.

The test field (90 x 16 m) was divided into 6 compaction areas with a length of 30 m (see Fig. 6). On the test areas for the roller with the polygonal drum the thickness of the remaining layer of the existing embankment body was varied (1.0, 0.75 and 0.50 m). The variation was made to find the optimum thickness of the remaining soil layer taking into account the compaction of natural ground underneath the formation level of excavation. Compaction was provided by a 12 ton variocontrol roller with polygonal drum. In two areas the fill material was completely removed and finally compacted in layers by a 12 ton vibrating roller with conventional smooth drum in order to compare the effect of different drum types.

Quality assessment of compaction was performed by roller-integrated continuous compaction control (CCC) as well as by punctual light dynamic probing (DPL) and dynamic load plate tests.

CCC values were documented after each roller pass until the compaction increase reached the required minimum value of < 5 %. The measured values of the vibration modulus E_{vib} showed a very homogenous compaction on the areas where the polygonal drum was applied. The average increase of the vibration modulus achieved during compaction with the polygonal drum of the existing embankment areas was between 42 % and 69 %. Although the measurements with the conventional drum indicated a higher compaction E_{vib}-values, the homogeneity of the compaction was not as good as gained with the polygonal drum. The high E_{vib}-values were primarily caused by the different machine parameters.

The relative density was performed by light dynamic probing (DPL) on selected spots for each compaction area before and after compaction. An increase of DPL-blows to a depth of about 1.5 – 2.0 m was observed on test areas compacted with the polygonal drum (see Fig. 7). The results of DPL-tests carried out on the fields compacted with the smooth drum showed an increase of blows to a depth of about 1.6 m (see Fig. 7). In addition to the DPL-tests also dynamic load plate test were carried out. The measure dynamic deformation modulus varied strongly in dependence of the soil parameters of the compacted fill material.

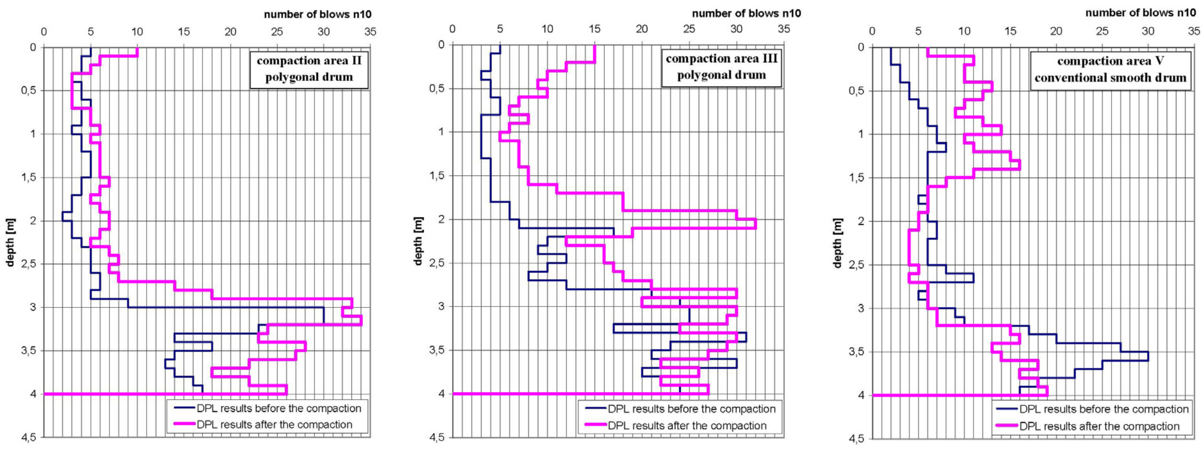

Fig. 7: Compaction control with dynamic probing light from selected compaction areas (polygonal drum: compaction area II and III; conventional smooth drum: compaction area IV.

The comprehensive measurements performed during the compaction tests show that an efficient compaction can be gained by the application of the polygonal drum. The structured drum shape causes a permanent kneading of the fine and/or mixed grained soil material with followed stress relief. This compaction technique provides a homogenous compaction over the entire compaction depth. The homogeneity was indicated by the CCC-plots.

Based on the interpretation of the tests results it can be noticed that the optimized compaction by the polygonal drum is technically equivalent to the original compaction concept to a maximum layer thickness of about 0.7 – (1.0) m above the formation level of excavation (see Fig. 8). The thickness of single layers can be increased for the embankment construction to increase the compaction depth in comparison to the conventional drum. An important economical effect is that time savings of the earth works are significant.

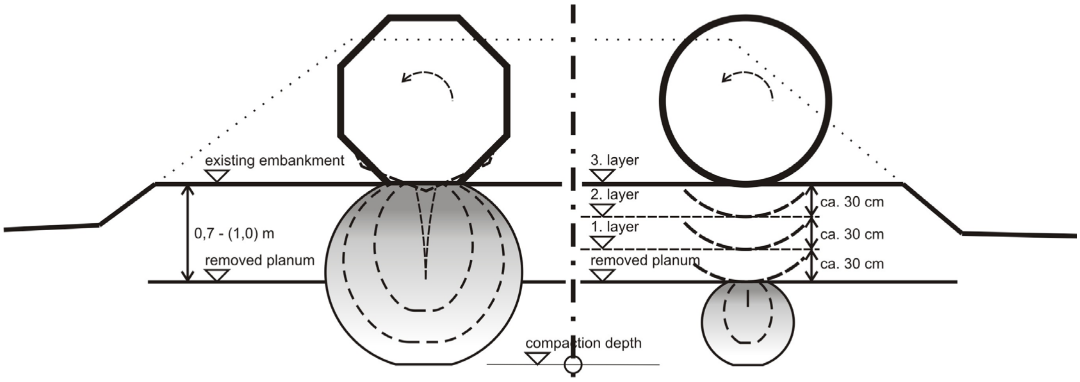

Fig. 8: Compaction effect of the polygonal drum in comparison to the conventional smooth drum.

5.2 Remediation of flood protection dikes using the RIC

The suitability of the Rapid Impact Compactor to improve existing flood protection dikes alternatively to e.g. the mixed-in-place method (MIP) was investigated by compaction of the core of a test dike. The compaction process and control at the test field are summarized in the following.

The test dike was constructed on a gravelly ground that is covered with loess layer of a thickness of about 0.75 m. The embankment base (about 14 m x 35 m) was compacted with a vibration roller and tested with dynamic load plate tests using the Light Falling Weight Device (LFWD).

The core of the embankment has been constructed in layers with a thickness of about 1 m. Each layer was only “precompacted” with a vibratory roller in order to simulate the weak compactness of existing old flood protection dikes. For one half of the embankment core sandy silt (loess) was used as filling material, for the other half silt (loam). The shoulders and slopes were constructed with sandy gravel. Figs. 9 and 10 show the geometry and dimensions of the test dike.

The working platform of the test field, i.e. the top of the embankment, was divided into four test sections with a length of about 5 m (see Fig. 10). Test section 1 and 2 were situated in the loam core of the test dam, section 3 and 4 in the loess core.

The construction parameters of the Rapid Impact Compaction were chosen as follows:

- Diameter of the impact food: 1.5 m.
- The primary grid comprised three equally spaced compaction points every test section.
- The secondary grid for test section 2 and 4 consisted of the two compaction points that were displaced by half of the diameter of the impact food.
- The compaction process comprised two respectively three passes on the primary grid (test section 1 and 4 respectively test section 3) and one pass on the secondary grid (test section 2 and 4). After every pass the compaction craters were filled with core material and compacted with a vibratory roller.

The compaction was performed with the following stop codes:

- stop code 1: total settlement (depth of the compaction crater) > 0.8 m
- stop code 2: number of blows per compaction point > 40
- stop code 3: final settlement of the last blow < 10 mm

Optimization and control of the compaction was realized by the following tasks and criteria:

- Meeting the stop code criteria.
- Work integrated documentation of the production parameters for each compaction spot, i.e. the number of blows, the final settlement from last blow, the depth of the compaction

crater, the compaction energy, and the average number of blows. The compaction parameters were monitored electronically for each compaction point during the compaction process and automatically documented (GPS controlled data acquisition).

- Performance of dynamic probing heavy (DPH) before and after compaction.
- Performance of dynamic load plate test using the LFWD before and after compaction.
- In-situ permeability tests using the BAT system.
- Performance of vibration measurements at the dam toe between test section 2 and 3.

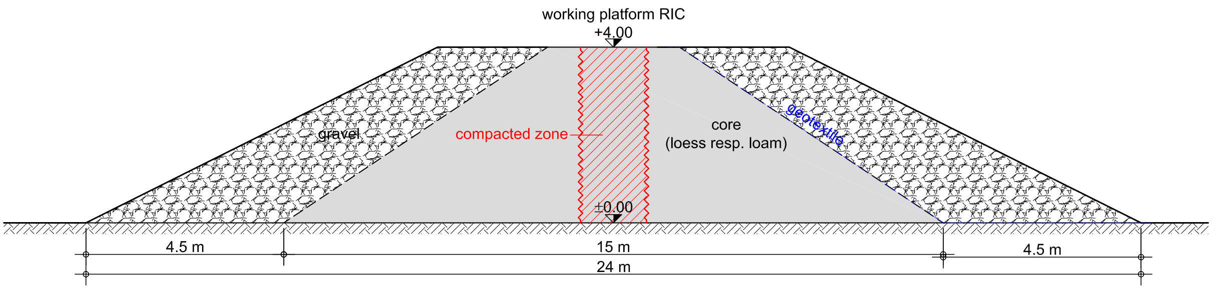

Fig. 9. Section of the test dam.

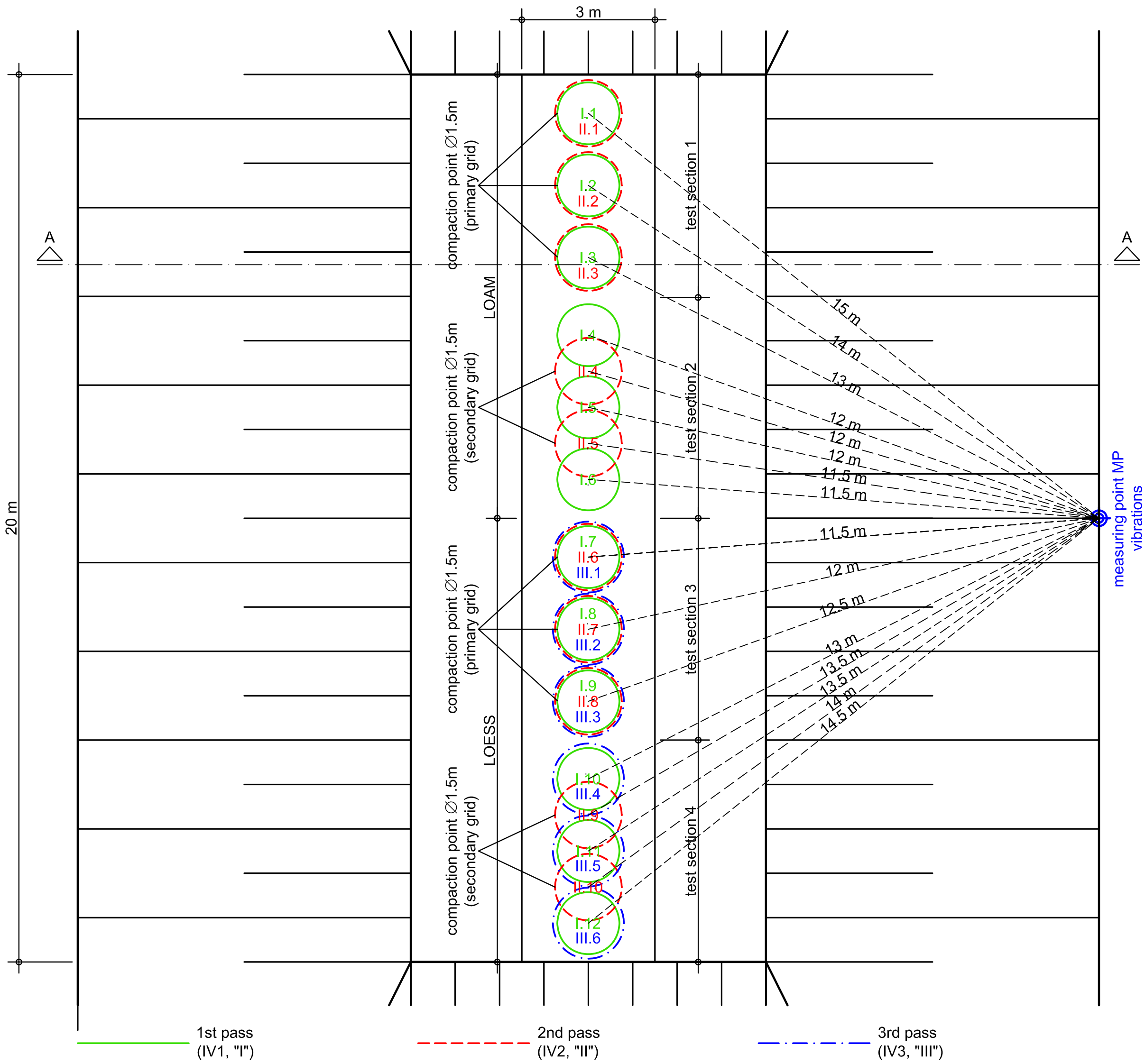

Fig. 10. Top view of the test dike.

In the following selected results of dynamic probing tests that were carried out to determine the compaction depth are presented exemplary. Fig. 11 illustrates the number of blows N_{10} over depth determined with dynamic probing heavy on test section 2 (loam) and 3 (loess). It is obvious that the depth effect of the RIC is about 4.5 m. Fig. 11 reveals that the upper zone of the gravelly ground beneath the embankment was compacted as well. While the improvement effect of the loess core is clearly reflected by the results of dynamic probing heavy, the increase of the number of blows in the loam core is not as significant. It has to be taken into account that the dynamic probing heavy allows only a low number of blows in cohesive soils comprising soft to stiff consistency independent of the degree of compaction. Consequently, for checking the compaction effect it is recommended to use dynamic probing light (DPL) or cone penetration tests (CPT) [8].

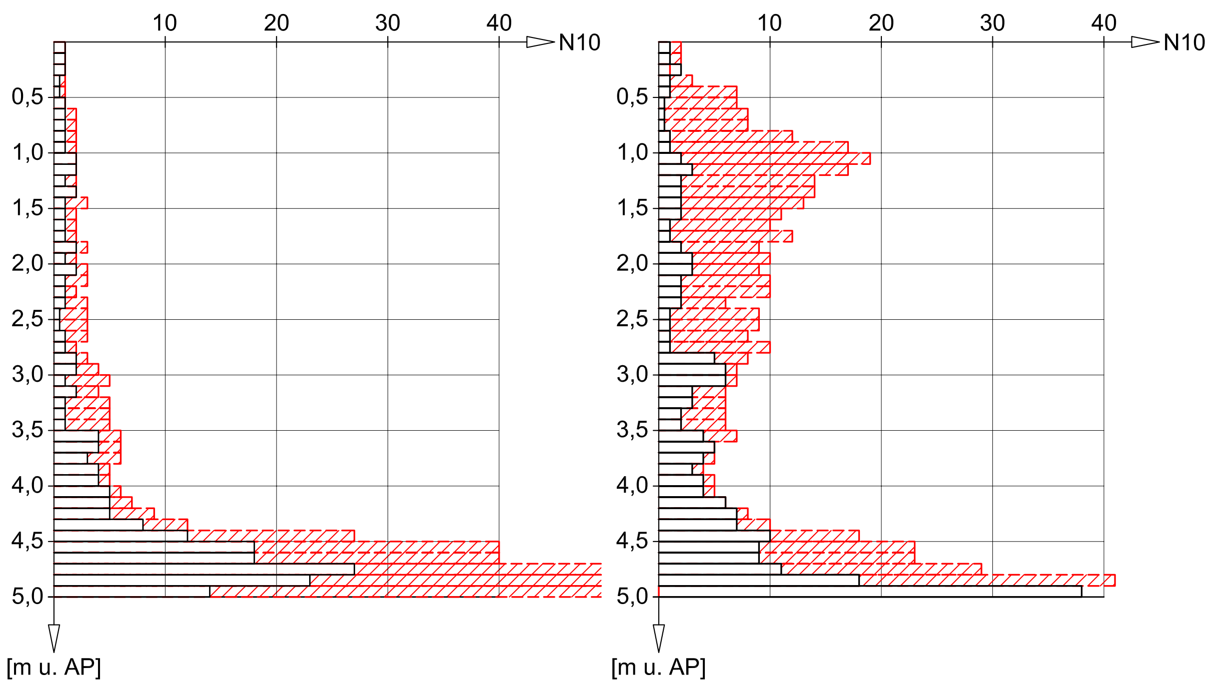

Fig. 11. Dynamic probing heavy (DPH). Comparison of the number of blows N10 before (black) and after (red) compaction with RIC on test section 2 (left) and test section 3 (right).

6. Conclusions

Investigations during the application of innovative compaction technologies (rollers with polygonal drum and Rapid Impact Compaction) for the rehabilitation respectively construction of flood protection dikes/dams revealed that a significant optimization can be achieved with respect to both the technical solution and the construction time.

The main advantages of the application of self-regulating (variocontrol) rollers with polygonal drum can be summarized as follows:

- The thickness of the compacted soil layer can be increased due to a better compaction effect and compaction depth in comparison to the conventional smooth drum. On the other hand the increase of layer thickness enables significant time saving for earth works.
- The drum shape causes a permanent kneading effect with followed stress relaxation what results into a homogenous compaction and better compaction effect. The soil particles are laterally shifted during the compaction whereby especially in fine grained soils the pore water pressure excess can be reduced faster. In this case also the tendency to consistency change by cohesive soils can be delayed.
- The penetration of the wedges into the ground produces a loosening of the layer surface. For this reason the crust effect arises later than by the compaction with the conventional

smooth drum and the compaction energy can by easily transferred into the deeper soil layers.
- The plates and wedges of the polygonal drum cause a uniform wash board pattern on the surface of the compacted layer. The pattern enables a good interlocking with superimposed soil layer.
- The roller-integrated continuous compaction control (CCC) is nowadays a standard measuring system of the most vibrating rollers and can by used for documentation, optimization and quality assessment also by application of the polygonal drum.

The improvement of flood protection dams by applying the Rapid Impact Compactor exhibits the following advantages:
- The Rapid Impact Compaction causes primarily the compaction of the treated soil and secondarily soil replacement. Thus, a significant reduction of the volume of the soil that has to be improved can be achieved. The reduced volume is substituted by a suitable filling material. Subsequent compaction passes result in a “cork” like improved zone respectively in a stirring of the filling material with the treated soil.
- Due to the reduction of the soil volume, i.e. the reduction of the void ratio, a dike/dam core of low permeability can be created. On the other hand existing cavities are completely closed and existing horizontal zone of higher permeability, e.g. stray sand, are destroyed.
- The application of the Rapid Impact Compaction produces an increase of the bearing capacity and the stability of the dam, and, thus, a reduction of the erosion risk.

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