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REFURBISHING EMBANKMENTS FOR FLOOD CONTROL BY IMPULSE COMPACTION – COMPACTION TECHNIQUE AND QUALITY CONTROL

Lienbacher, F.[1], Chwatal, W.[2], Fürpass, J.[3], Schön, H.[4], Wu, W.[1]
[1]Institut für Geotechnik, Universität für Bodenkultur, Wien, Austria
[2]Institut für Geodäsie und Geophysik, Technische Universität Wien, Austria
[3]Terra-Mix GmbH, Wettmannstätten, Austria
[4]Teerag-Asdag AG, Krems, Austria

ABSTRACT: As a consequence of the flood in 2002, two embankments in the federal state Lower Austria were refurbished in 2009. The refurbishment was realized by Impulse compaction. This innovative method for soil improvement and the quality control for the optimal application is described in this paper. In addition to the conventional compaction control by dynamic probing, some geoseismic measurements were carried out. The results of the seismic measurements and the dynamic probing were compared.

1. Introduction

The embankments are situated at the river Kamp in Lower Austria. The river with a length of about 160 km flows through the north-western part of Lower Austria to merge into the river Danube in Altenwörth. The project area is situated near Jettsdorf about 60 km from Vienna near the merging area of the river Kamp with the Danube (see black dot in Figure 1).

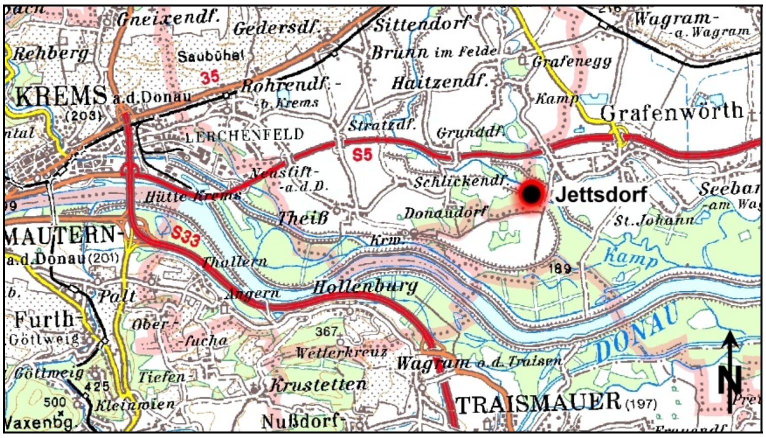

Figure 1: Map of the project area, modified from (AmapAustria)

The embankments on both sides of the river Kamp were constructed in diverse time periods. Some parts of the dams are more than 100 years old. In August 2002 the project area was devastated by two extreme floods. Precipitation reached from 160 mm up to more than 200 mm within two days (Godina, et al., 2004). The first flood was registered on August 8th and the second on August 13th. The high-water level combined with the poor condition of the embankment lead to dam failures at several locations which caused a flood in this area (see Figure 2).

Figure 2: Picture of the flood in Jettsdorf in the year 2002 (Gedersdorf, 2002)

Thereafter a feasibility study was started in 2002 and completed in 2005. This study investigated if the embankments for the lower part of the Kamp-region could protect this area from floods with a recurrence period of 100 years. It showed that the reactivation of retention areas near the river (behind the existing embankments) is the best possibility. Moreover the study suggested that the existing embankments should be refurbished. Based on this study it was decided to refurbish the embankments with possible overtopping areas along both banks with a total length of 4.9 km.

The construction started in 2009. In Figure 3 the two existing embankments on both sides of the river are shown. The levee on the right side of the river has a length of 2.4 km and that on the left bank 2.5 km. In the tender design, a conventional soil improvement method was considered. The contractor consortium presented an alternative to the usual Deep Compaction Method, which is the Impulse Compaction Method by "Terra-Mix GmbH".

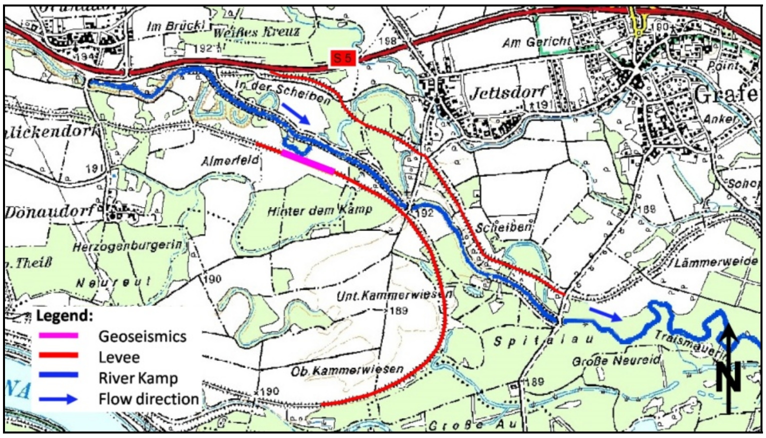

Figure 3: Investigation area; see legend for main features, modified from (AmapAustria)

2. Impulse Compaction

The Impulse Compaction Method is a modification of the dynamic consolidation with high energy input. The impulse is generated by a falling weight impacting on a cylinder placed on the ground surface. For this project a falling weight of 9 tons and a falling height of about 1.2 m were used. This cylinder is about 1.5 m in diameter and has a weight of three tons. According to previous experience with compaction work for road projects, an effective compaction depth of up to 7 m can be expected. The compaction depth of sandy soils is larger than for cohesive soils.

During the compaction work the relevant data are recorded:

- Date and time

- Location (GPS-coordinates)
- Settlement per impulse
- Total settlement
- Settlement curve
- Number of impulses
- Energy input

These data can be provided in table and graph via mobile internet connection. Thereby different settlement characteristics can be recognized and treated correspondingly in order to achieve a homogenous compaction result (Terra-Mix, 2009).

As the Impulse Compaction is a new technique in Europe, exact documentation and a strict quality control is necessary. For this purpose a trial run in a short section of about 50 m was carried out. The soil condition of this trial section was rather poor. Figure 4 shows the trial section with the impulse compactor.

Figure 4: Impulse Compaction at the trial section (DI Zehetner, 2009)

The following in-situ tests were carried out for compaction control:

- Dynamic probing light (DPL)
- Dynamic probing heavy (DPH)
- Dynamic plate loading test
- Nuclear density gauge
- Vibration measurements during compaction
- Deformation measurements of embankment

Furthermore, a test pit was excavated and a borehole was drilled. Some permeability tests and soil samples completed the tests. The extensive tests provided sufficient information of compact quality and compaction depth. The trial run helped to assess the effectiveness of the Impulse Compaction, as this is applied to embankment refurbishment for the first time.

The Impulse Compaction caused soil compaction with large soil displacement. Further the displaced space was filled with appropriate soil material, so the permeability of the embankment was reduced. Existing voids could be closed. The stability against erosion failure was improved. Moreover, the soil strength was increased, which gave rise to higher stability of the embankment slopes.

The working procedure of Impulse Compaction includes the following steps. Before starting compaction, the topsoil has to be removed so that the compactor can be placed on solid ground. The compaction machine worked at prescribed compaction points along the 50 m long trial section (first passage). The compaction work was performed in several passages until the compaction requirements were reached. In the craters created by the first passage a second compaction passage was carried out. Afterwards the craters were filled with appropriate soil before the third passage was performed. The craters were filled with an excavator and the whole trial embankment section was compacted with a roller. Finally the topsoil was replaced to enable grass growth. The soil used to fill the crater was silty sand with some gravel fraction. This material can be easily compacted and possesses a low permeability. The trial section confirmed, that the Impulse Compaction Method is suitable to improve the existing embankment and is at least equivalent to the conventional compaction methods (Adam, 2009).

3. Dynamic Probing light (DPL) and heavy (DPH)

Impulse Compaction Method finally was applied with the operation method which was compiled by the trial section. Dynamic probing was chosen to ensure the achievement of the Impulse Compaction Method. Site supervision decided to explore the Kamp levee with dynamic probing every 200 m. It was started with 14 DPH-stations on the right levee with a sounding depth of 9 m. DPL were also done on the first 6 stations (with a distance of 10 m) in order to compare number of blows of DPH with DPL.

Figure 5 compares the averaged results of DPH with DPL on the first 6 stations. The lines show the logarithmic number of blows of DPH and DPL per 10 cm until 5 m depth. Sounding lines after the Impulse Compaction start at 0.1 m depth, caused by the removal of the topsoil for the working level of the Impulse Compaction Machine. It can be seen that DPL has the higher resolution in critical depths in 1.0 to 1.5 m.

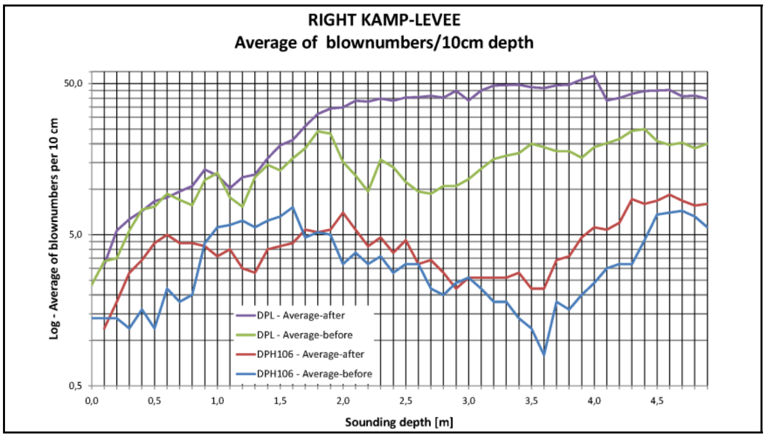

Figure 5: Right levee - comparison of DPH and DPL (before and after Impulse Compaction) averaged from 6 stations

Figure 6 shows the result of DPH on average of all 14 stations on right levee. The blue line shows the number of blows before and the red line the increase of blows after the Impulse Compaction. The lines illustrate a critical part in 1.0 to 1.5 m depth too, but as Figure 5 showed this might depend on less resolution of DPH.

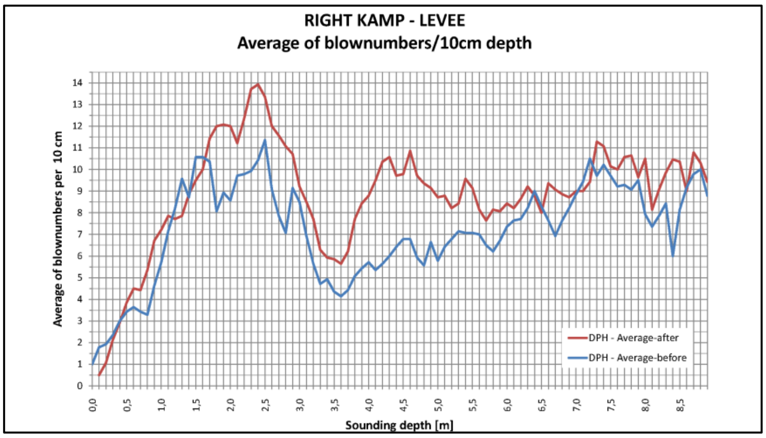

Figure 6: Right levee - result of DPH (before and after Impulse Compaction) averaged from 14 stations

It was decided to use 15 DPL on the left levee because of the higher resolution. Figure 7 shows the result on average of the 15 stations from the left levee. The blue line gives the number of blows before and the red line after the Impulse Compaction. A critical part is shown also in a depth between 0.5 -1.0 m. Below this depth the DPL shows a highly increased number of blows.

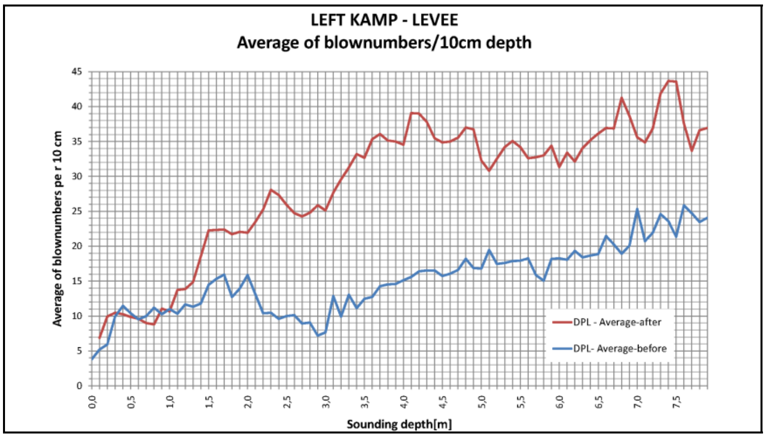

Figure 7: Left levee – result of DPL (before and after Impulse Compaction) averaged from 15 stations

The analysis of dynamic probing was done by averaging the blow numbers for every 10 cm. Outliners (with high number of blows simply because of boulder) were identified through standard deviation and not used for average determination.

4. Geoseismics

The investigation with geoseismics was carried out in cooperation with the Institute of Geodesy and Geophysics at the Vienna University of Technology. The field work was performed with Pöyry Infra GmbH. To determine if there is improved density of the dam body, seismic measurements were carried out before and after the Impulse Compaction.

Figure 3 shows the area of the seismic measurements. This area was chosen because the river flows close to the levee and the dynamic probing showed rather low numbers of blow, a clear indication that the embankment condition was rather poor. The seismic data acquisition began with the generation of seismic waves which was done in our case by a sledgehammer (shot). The recording of the seismic waves (ground motion as a function of the time) took place along a line on the dam via 48 receiver arrays, which were planted in equal spacing of 2 m. Each receiver array consisted of four single geophones with a natural frequency of 10 Hz (see

Figure 8). The signals of the geophones were stored in a portable registration unit (SUMMIT COMPACT).

Figure 8: Geophone arrays are linearly deployed on dam-surface, with a receiver spacing of 2 m

The seismic measurements were carried out according to the roll-along acquisition method, where the source was at the first receiver. The whole seismic arrangement moved step by step from one geophone station to the next (see Figure 9). Thus, the total length of the seismic line was about 300 m. Special attention for the data acquisition was given to acquire surface waves. The field records were analyzed with the seismic refraction and seismic surface wave method.

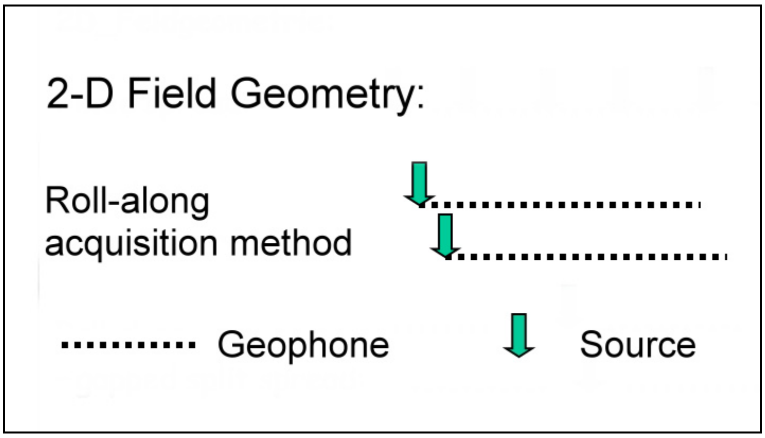

Figure 9: Roll-along acquisition method for geoseismic survey

Seismic Refraction

Refraction waves are special body waves (P- or S-wave) which spread from the seismic source to a stratum with higher wave velocity than the overlaying layer and then propagate along the border of this layer sending energy back to the ground surface. Figure 10 shows the propagation paths of the direct and refracted waves and the typical distribution of the velocities of the layers.

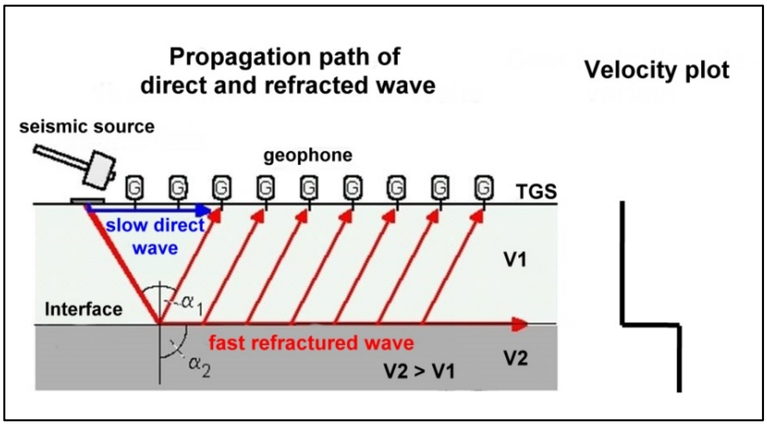

Figure 10: Detection of refraction wave, modified from (GGU-Karlsruhe)

In our case the refraction layer with a velocity about 2000 m/s is interpreted as the groundwater level in about 5 m depth. Near the source the direct wave is observed which propagates as a body wave along the ground surface. The velocity of the direct wave is valid from the ground surface to the depth of the refraction layer and stands for the dam density.

Figure 11 shows one result of the refraction seismic, the velocity of the direct wave, before and after the compaction. The black and the red line display the velocity of P-waves (primary or pressure waves). The grey and the orange line show the velocity of S-waves (secondary or shear waves). Both waves indicate an increase of velocity. The average seismic velocity for the whole seismic line shows that the velocity of P-waves increase from 346 m/s to 394 m/s and the velocity of S-waves from 142 m/s to 173 m/s. This increase in seismic velocity indicates that the density of the embankment body increased as well.

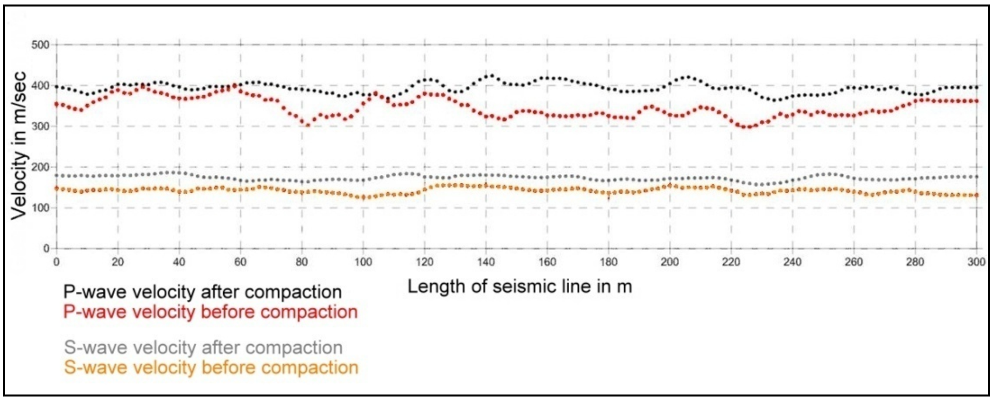

Figure 11: Outcome from refraction seismic

Surface waves

Surface waves (here Rayleigh waves) propagate dispersive along the ground surface. This means that with lower frequency the penetration into the subsurface becomes greater. The result of the surface wave analysis is a 1-D shear wave velocity function with depth for each shot which has a high resolution near the ground surface. For our purpose Multichannel Analysis of Surface Wave (MASW) was used to get information about the increase of density in the subsoil beyond the groundwater-level. This method consists of the following steps:

1. Acquisition of a multiple number of multichannel records along a linear survey line by use of the roll-along mode
2. Processing all acquired records independently to produce a 1-D (depth) Vs profile for each record
3. Creating the 2-D Vs map through spatial interpolation by assigning each 1-D Vs profile at the surface coordinate in the middle of the receiver spread used to acquire the corresponding record (Park, 2005).

Figure 12 shows a fundamental dispersion curve for one shot. The extraction of this curve is a critical step in the surface wave analysis.

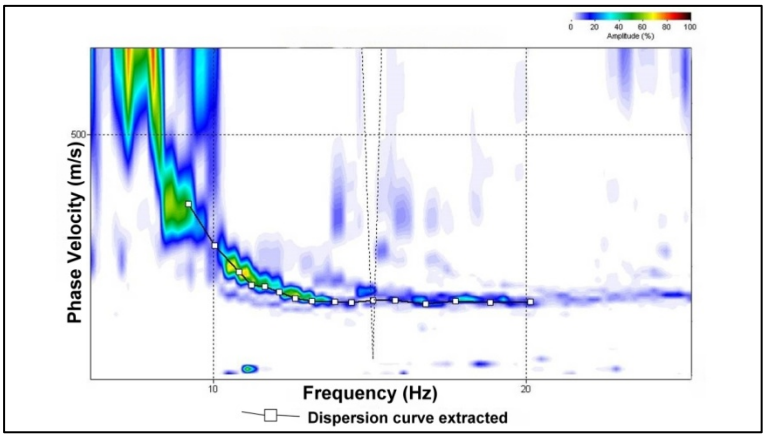

Figure 12: Extraction of the fundamental-mode dispersion curve

The dispersion curve is the hallmark of surface waves. This curve shows the typical connection between phase velocity and frequency for surface waves (Rayleigh waves). Body waves (i.e. P- and S- waves) are independent of the frequency. Figure 13 illustrates the result of the second step in MASW, the 1-D shear-wave velocity as a function of the depth (blue continuous line).

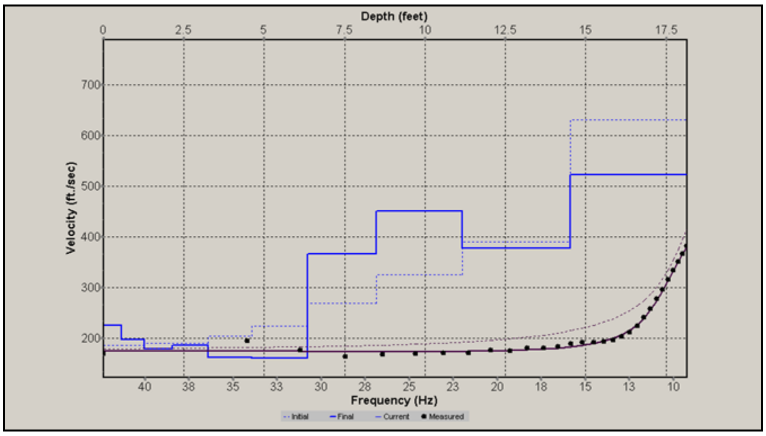

Figure 13: 1-D (depth) Vs profile for one record (blue line)

Figure 14 shows the 2-D shear-wave velocity along the whole seismic line. The upper figure shows the velocity before and the lower one after the Impulse Compaction. The upper picture presents a decrease of the seismic velocity in 2–3 m below ground surface. The reason for this decline may be due to the historical development of the embankment. The lower figure shows an increase in this critical section.

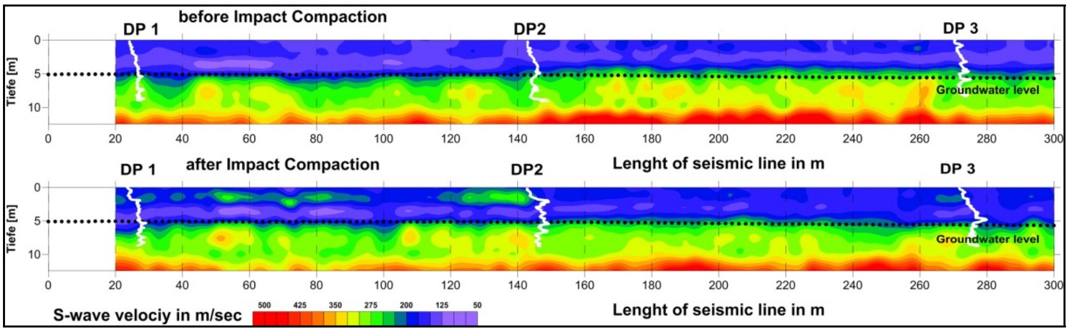

Figure 14: 2-D shear velocity with groundwater-level (black doted line) in 5 m depth compared with the results of DPL (DP 1-3)

Figure 15 shows the average S-wave velocity over the whole seismic line before and after the Impulse Compaction calculated from the MASW. It can be clearly seen that the S-wave velocity increased down to 3.5 m depth. Below 3.5 m there is virtually no difference in the seismic velocity. This finding suggests that the effective depth of the Impulse Compaction is about 3.5 m.

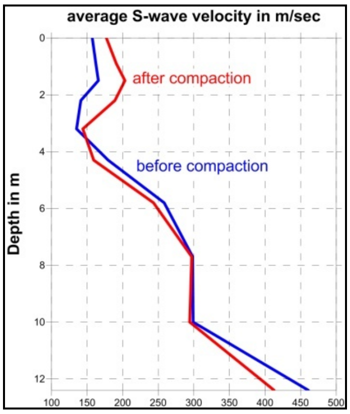

Figure 15: Average S-wave velocity from MASW over whole seismic line

5. Conclusion

Impulse Compaction, an innovative method for soil improvement, was applied for refurbishing embankments for flood control in a project. A combination of DPH and DPL was used for compaction control during this project. As an attractive alternative, geoseismic measurements were carried out in a short embankment section.

The Impulse Compaction Method was shown to be a competitive method for soil improvement. Significant improvement was achieved for the embankments sections with poor condition and weak spots. The improvement was clearly demonstrated by the results of the surface seismic analysis. The seismic measurements were well corroborated by the conventional dynamic probings.

The surface seismic analysis provides an attractive method for compaction control. As compared with the conventional methods, e.g. dynamic probing, the surface seismic analysis has the definite advantage of being continuous and fast. With surface seismic the weak spots within the embankment with very low density can be easily localized, while for dynamic probing this is often a matter of chance.

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