DESIGN AND EXECUTION OF SOIL MIX WALLS FOR RETAINING STRUCTURES

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ABSTRACT

In the last twenty years, Deep Mixing has increasingly been used for the construction of retaining walls. This has become possible due to new developments in the field of mixing equipment and the composition of the injected binding agents allowing to achieve satisfactory strengths for the soil mix material. At the DFI Deep Mixing conference of San Francisco 2015, the works of the Belgian Building Research Institute (BBRI) to develop guidelines for that application were presented. This effort resulted in 2018 in the publication of the BBRI/SBRCURnet Handbook - Soil mix walls. The present keynote presents the design philosophy followed in this handbook for the realization of the soil mix walls. After presenting constructive aspects, the following design topics are particularly highlighted: the verification of the arching effect, the composite bending stiffness and the bending resistance according to the rules of the Eurocodes, the building codes for Europe. Finally, an example calculation of the moment capacity is also given.

Keywords: design, soil mix walls, retaining walls, arching, bending stiffness, moment capacity

INTRODUCTION – EXECUTION OF SOIL MIX WALLS AND WORKING PRINCIPLE

Since 2000, the soil mix walls have become increasingly popular in Belgium and the Netherlands for the construction of retaining structures. In practice, however, there was a lack of a generally accepted approach to design such structures. It was necessary to define functional requirements, design rules for the soil mix material and for the wall itself including a safety philosophy. There was also a need for criteria for the execution and the quality control of the works. Moreover, as the soil mix walls are often used with a permanent function, recommendations for the management and the maintenance of such walls on the long-term would bring an added value for the sector. This is the reason why designers and contractors have been asked to pool knowledge and experience with soil mix walls. The result was the BBRI/SBRCURnet Handbook Soil mix walls published in 2018 and referred as the handbook in the present keynote.

In the deep mixing, the ground is mechanically mixed in place and in depth by an auger or a cutter machine, while a binder, often based on cement, is injected. Due to hydration reactions, the soil□cement mixture, called soil mix material, progressively hardens in the ground. In Belgium, the main application of the deep mixing is the construction of retaining walls which can be braced or anchored and can support the earth and water pressures in function of the circumstances (see Fig. 1 to 5). The construction of retaining shafts (i.e. silo structures) is possible (see Fig. 6). Soil mix walls can be installed with single or multiple shaft systems producing soil-cement columns (see Fig. 7 to 13), with the Cutter Soil Mixing (CSM) system for the construction of rectangular panels (see Fig. 14 to 16) or with a trench cutter device realizing a soil mix trench in one single continuous pass in the ground (see Fig. 17) but the latter is less ordinary in Belgium. The execution is performed according to the European standard EN-14675. In order to build soil mix walls for the realization of an excavation, the soil mix elements (columns or panels) are placed next to each other, in a secant way (see Fig. 18). Installation depth of more than 20 m can be achieved. The diameter of the soil-cement columns generally ranges from 0.4 to 0.6 m. The typical length of the CSM panel ranges between 2.2 to 2.8 m with a thickness of 55 cm. By overlapping the different soil mix elements, a continuous retaining wall is built. The wall is then horizontally stabilized with the help of bracing or anchoring systems. During execution, steel H or I-beams are generally installed in the fresh soil mix material to resist the shear forces and bending moments due to the pressure applying on the wall. The soil mix material mainly transmits the stresses due to this pressure to the steel beams by way of an arching effect developing in the soil mix due to the difference of stiffness between the steel and the soil mix material.

Fig. 1. Braced soil mix wall (made with the CSM technique) used as retaining structure for the realization of an excavation (with the courtesy of Bauer Nederland)

Fig. 2. Braced soil mix wall (made with soil-cement columns) used as retaining structure for the realization of an excavation, the bracing is performed after milling the soil mix surface (with the courtesy of Michał Topolnicki - Keller)

Fig. 3. Enlarged view of an anchored soil mix wall (made with the CVR C-mix® technique) used as retaining structure for the realization of an excavation (with the courtesy of CVR nv)

Fig. 4. Anchored soil mix wall (made with the CSM technique) used as retaining structure for the realization of an excavation (with the courtesy of Lameire funderingstechnieken nv)

Fig. 5. Anchored soil mix wall (made with the TSM technique) used as retaining wall for the realization of an excavation and underpinning of an existing building (Smet F&C)

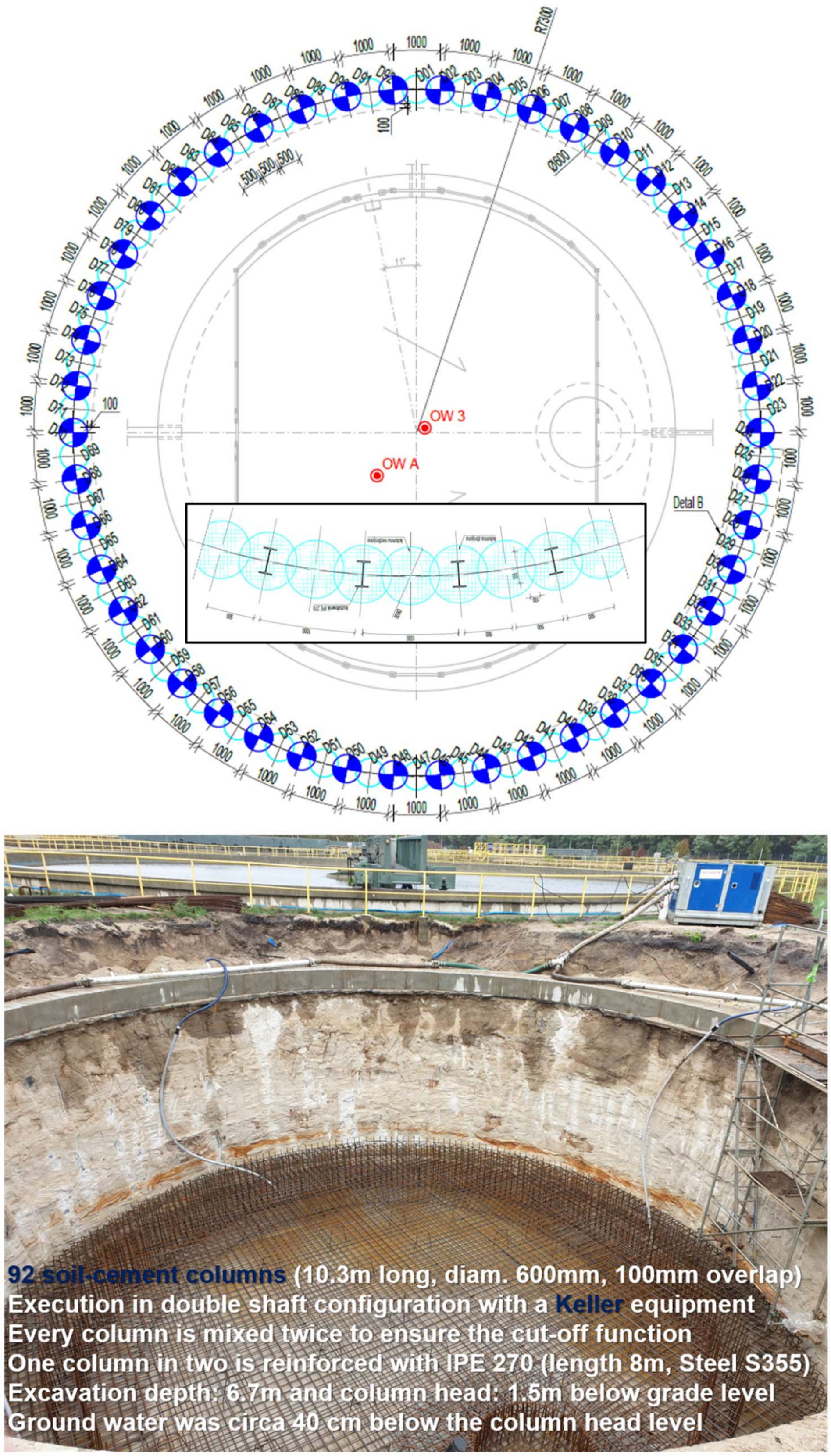

Fig. 6 – Soil mix shaft made with soil-cement columns for a sewage treatment plant (with the courtesy of Michał Topolnicki – Keller)

Fig. 7. Picture of a drilling/mixing head used for the execution of soil-cement columns in single shaft configuration (with the courtesy of Michał Topolnicki - Keller)

Fig. 8. Picture of a drilling/mixing head used for the execution of soil-cement columns in single shaft configuration (with the courtesy of ABI)

Fig. 9. Execution of secant soil-cement columns with an ABI drilling/mixing head – execution in single shaft configuration (with the courtesy of Franki Foundations – group Besix)

Fig. 10. Execution of soil-cement columns with the Tubular Soil Mixing (TSM) technique – execution in single shaft configuration (with the courtesy of Smet F&C) – the external shaft is used to ensure the geometry of the final column in case of high mixing energy (up to 500 bars)

Fig. 11. Execution of secant soil-cement columns in double shaft configuration with two ABI drilling/mixing heads (with the courtesy of Franki Foundations – group Besix)

Fig. 12. Execution of secant soil-cement columns in double shaft configuration (with the courtesy of SMET F&C)

Fig. 13. Execution of secant soil-cement columns in triple shaft configuration (with the courtesy of SMET F&C)

Fig. 14. Execution of a soil mix wall with secant panels performed with the CSM technique – the cutters are mounted on a cylindrical kelly (with the courtesy of Lameire funderingstechnieken nv)

Fig. 15. Execution of a soil mix wall with secant panels performed with the CSM – the cutters are mounted on a square section kelly (with the courtesy of Soetaert nv – group Jan De Nul)

Fig. 16. Enlarged views of the cutter system of a CSM machine used for the execution of soil mix panels (with the courtesy of Soetaert nv – group Jan De Nul)

Fig. 17. Trenchmix system of Soletanche-Bachy/Mastenbroek used for the realization of soil mix wall in one single continuous pass (with the courtesy of Soletanche-Bachy)

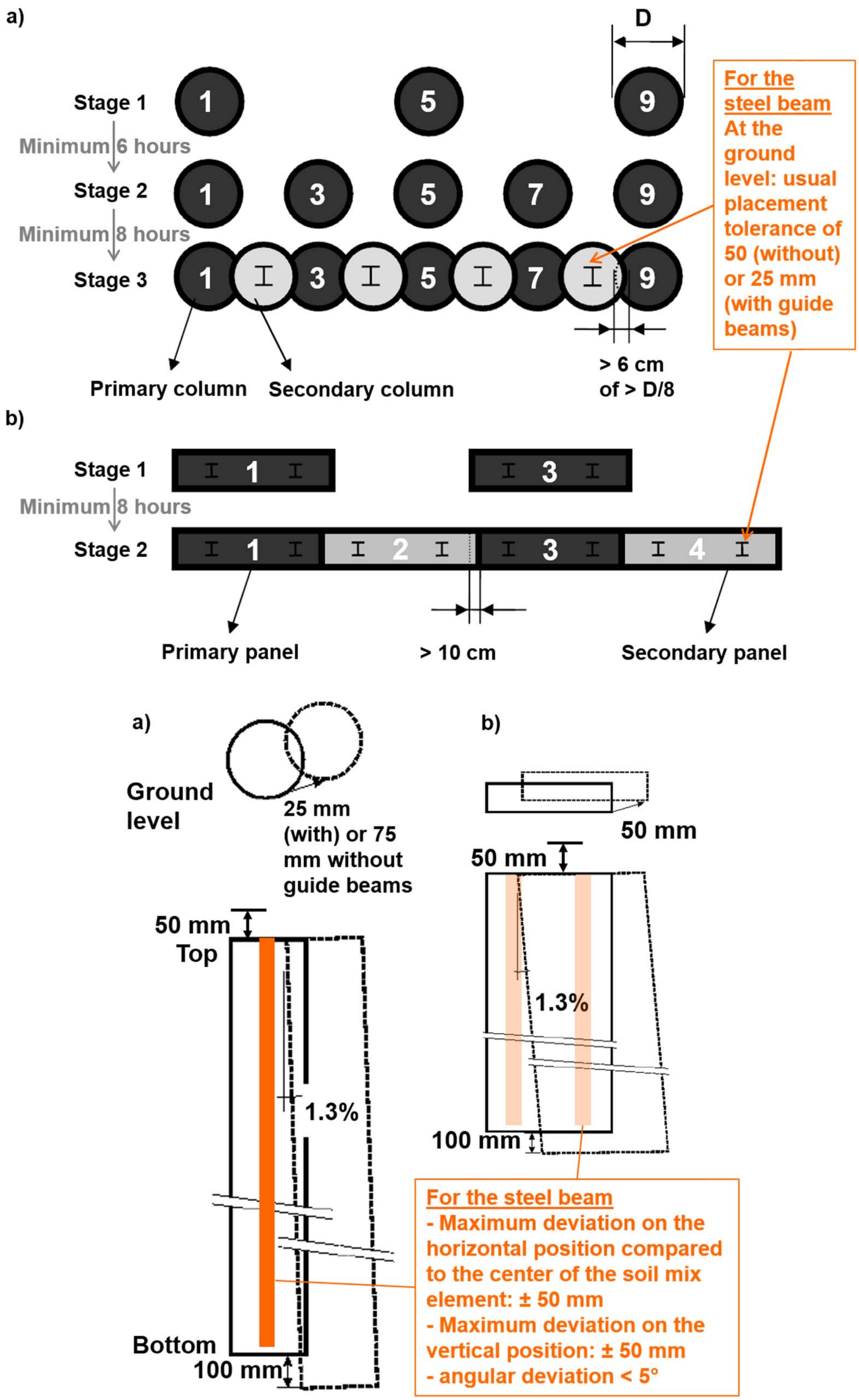

Fig. 18. Execution sequence and tolerances for soil-cement columns (a) and soil mix panels (b) - With multiple shaft configuration systems, a larger spacing can be considered (cf. handbook)

Figure 19 illustrates the working principle of a retaining wall made of soil mix. As shown by the results of seventeen large-scale bending tests, performed on real soil mix elements excavated from construction sites, the soil mix material also plays a role in the bending stiffness and contributes to the moment capacity of the retaining wall (see Denies et al. 2014 and 2015).

During execution, contractors can use cords (see Fig. 16), steel guide frames (see Fig. 20) and concrete beam with reservations made of expanded polystyrene (see Fig. 21) to reach the execution tolerances. Control with lasers is also performed.

If there is limited space for the construction, the wall thickness may be reduced. After excavation, this can be carried out by means of a milling cutter (see Fig. 22) and more space becomes therefore available for the construction of, for example, a basement/cellar. Milling is also performed to connect the basement and building floors in the soil mix wall. With milling operations, the focus points are the covering of the steel beams and the effect of the reduction of the wall dimensions on the design of the soil mix wall. Leveling (milling of the upper part of the wall) can also be performed to install a concrete head beam on the wall.

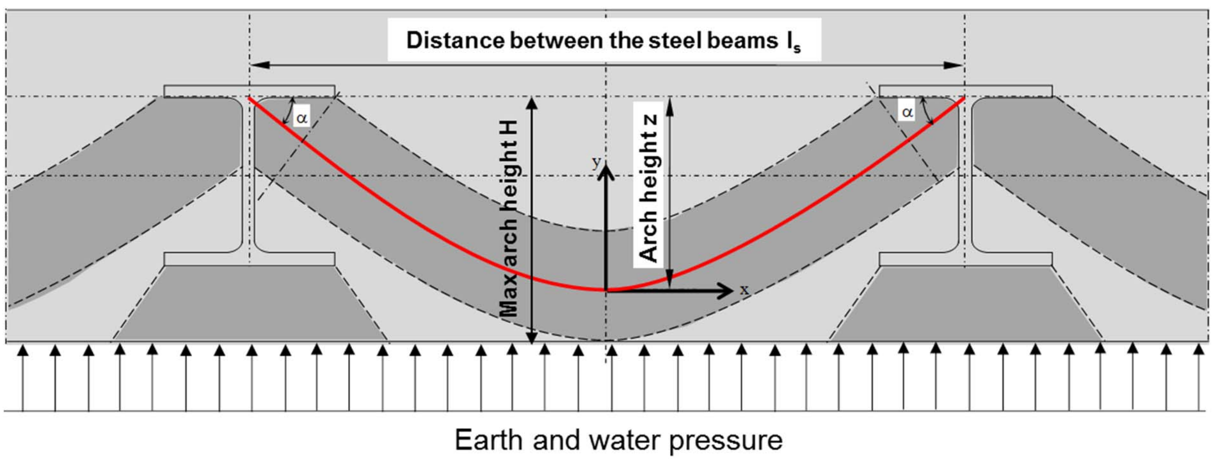

Fig. 19. Working principle of a soil mix retaining wall and illustration of the arching effect

Fig. 20. Guide frames (left): used to reach the execution tolerances for the alignment of the soil mix panels executed along the horizontal steel beam; and (right): for the positioning of the steel beams in the soil mix material after extra steel frames are attached to the horizontal beam (Pictures with the courtesy of Hoffmann)

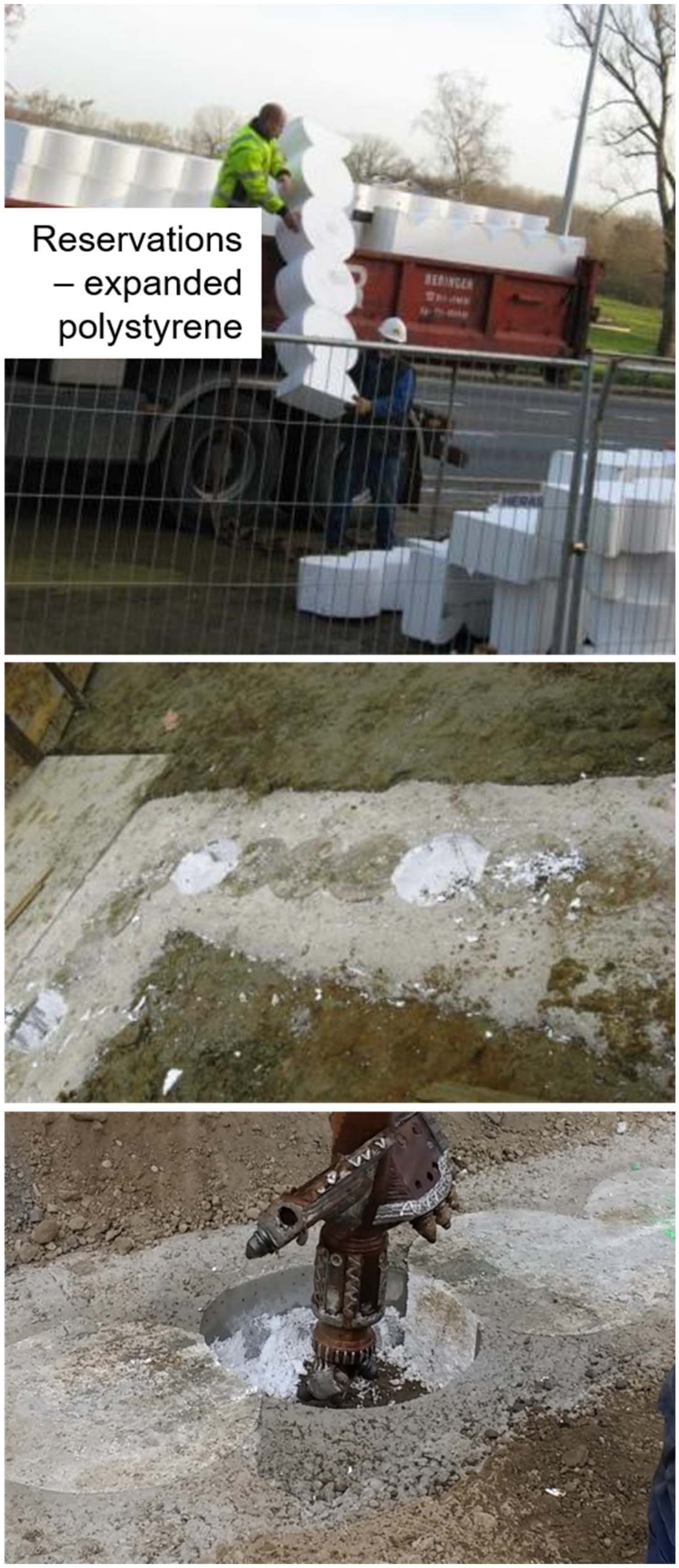

Fig. 21. Concrete beam with reservations (filled with expanded polystyrene) used to reach the execution tolerances for the alignment of the soil-cement columns

Fig. 22. Milling of the surface of the soil mix material of a soil mix wall made of CSM panels

The horizontal support/stabilization of the wall is realized with the help of purlins. A local transfer of the force with, e.g. an anchor seat, is also possible. In this case, the ground anchors can be placed between or at the location of the steel beams. Figure 23 gives an example of horizontal support of a soil mix wall stabilized by an inclined anchor embedded in the soil mix material. Other horizontal support solutions are illustrated in the handbook. The verification of the potential punching failure mechanism must be performed regarding the horizontal support solution.

As illustrated in Fig. 24, in practice, soil mix walls are often installed along/in the vicinity of existing buildings. The wall can be installed very close to or against existing foundation elements. No important vibrations are caused by the deep mixing operations and as the stress relaxation of the soil is limited, soil mix walls can be executed nearby existing constructions. Nevertheless, the influence of installing the soil mix wall along existing structures must be assessed for each individual case and before the start of the works. Soil mix walls near foundation elements are usually not realized in one continuous pass. If a soil mix wall is executed near foundation piles and is installed below the level of the pile base, specific study must be conducted to verify the stability of the piles. Soil mix walls can also be installed along existing slope (see Fig. 25). In this case, the influence of that installation on the slope stability will be studied and an adapted discontinuous execution sequence will be adopted.

During execution, process parameters should be monitored and registered as specified in the European standard EN 14679 for the execution of the deep mixing. According to this standard, the following construction parameters and information shall be monitored continuously during execution, or at least at a depth interval of 0.5 m: slurry pressure, air pressure (if relevant), penetration and retrieval rate, rotation speed (revolutions/minute during penetration and retrieval) and quantity of slurry per meter of depth during penetration and retrieval.

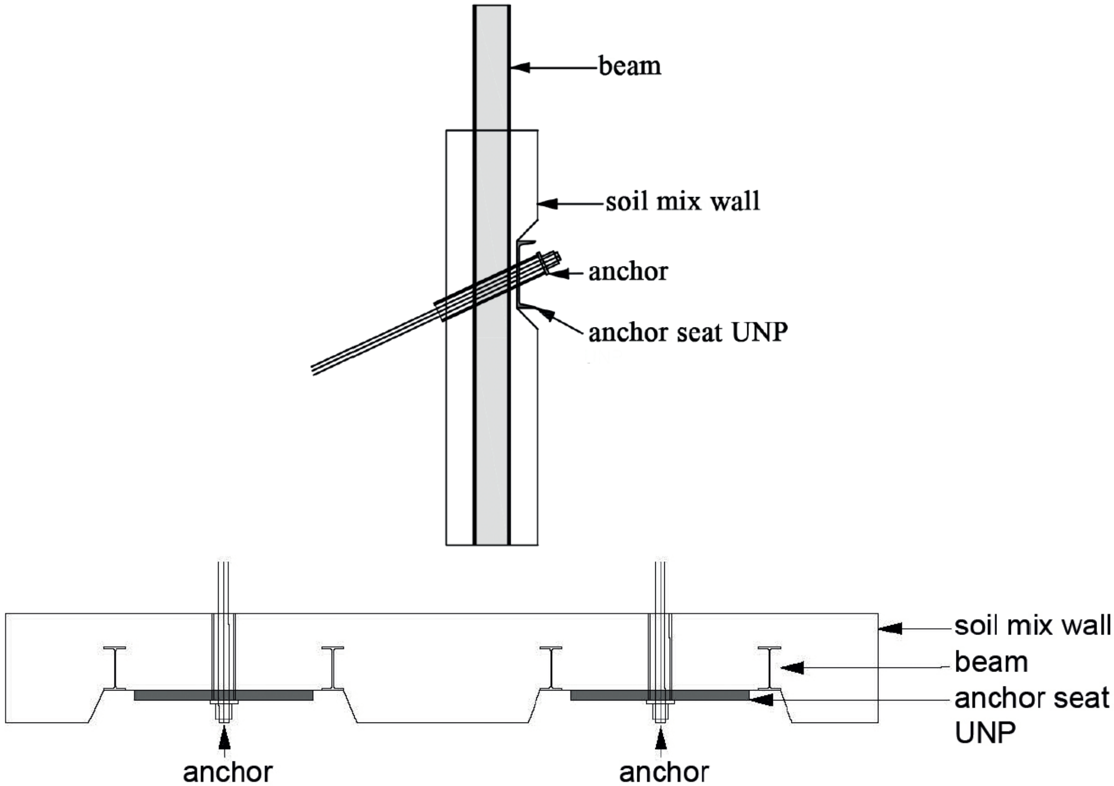

Fig. 23. Example of principle scheme for the horizontal support/stabilization of a soil mix wall with an inclined anchor embedded in the soil mix material (handbook)

Fig. 24. Execution of a soil mix wall (CSM technique) along existing foundations

Fig. 25. Execution of a soil mix wall along an existing slope

In the European standard EN 14679, the slurry is defined as the injected grout made of water, binders with or without fillers and admixtures. It is also called (cement) grout or injected water-binder mixture in practice. The handbook provides an exhaustive list of process parameters to be registered during execution. A distinction is also made between parameters that must be checked once and parameters that must be checked continuously or at a regular interval.

Whatever the equipment, the soil mix process developed and proposed by the deep mixing contractor must present a good production rate and must be competitive regarding typical concrete solutions. It is not only a question of mixing the soil in place with a water-binder mixture but also to ensure that:
- the fresh mixture (water-binder-admixtures-soil) presents a sufficient workability,
- the embedment depth of the soil mix elements is reached with the deep mixing equipment,
- the drilling/mixing head is retrieved without difficulty once the final depth is reached,
- a steel beam can be installed in the fresh soil mix material after execution and that until the determined depth of installation and regarding the execution tolerances,
- the soil mix material is homogeneous (i.e. limited percentage of unmixed soft soil inclusions) and presents, after setting and hardening, the strength, stiffness and permeability required in the job specifications or encountered in the general practice of soil mix walls,
- a competitive production rate is reached regarding the other deep mixing contractor/system and regarding the typical concrete solutions.

For the purpose of answering these requirements, the deep mixing contractor will select the minimum binder content (mass of cement per volume of mixture) - in order to reach a sufficient strength – and will define the water/binder weight ratio of the injected grout – to obtain a sufficient workability without decreasing the strength of the soil mix material –.

The binder content varies in function of the design. In Belgium, for common retaining walls, it still ranges between 350 to 500 kg/m³. But higher values are possible in function of the loads. The water/binder ratio generally varies between 0.6 and 1.2 depending on the soil type, the water content of the soil and the design function(s) of the wall. A water/cement ratio of 1 (-) is often encountered in Belgium in loamy, silty and clayey soils. Similar (or smaller) value can be used in sandy soils.

Another governing parameter is the mixing energy. The degree of mixing will be proportional to this energy. With shaft configuration systems, presenting a vertical axis rotation for the mixing tool, this energy can be quantified with the help of the Blade Rotation Number (BRN), which is computed considering the geometry of the tool and the way the mixing is performed into the ground. The BRN can be defined as the total number of revolutions (rev) carried out by the mixing blades of the soil mix tool per meter of soil penetrated during the process. It can be expressed as:

$$BRN = M\left(\frac{R_p}{V_p} + \frac{R_w}{V_w}\right) \qquad [1]$$

where BRN is the Blade Rotation Number quantifying the mixing energy (number of revolutions per meter), M is the total number of mixing blades (-), R_p is the rotational speed of the mixing tool during penetration (rev/min), V_p is the penetration velocity (m/min), R_w is the rotational speed of the mixing tool during withdrawal (rev/min) and V_w is the withdrawal velocity (m/min).
Topolnicki (2004) provides exhaustive explanations and complete definitions of the BRN.

The determination of the mixing energy is very important in the development and the mastery of a competitive and efficient deep mixing process. A too weak mixing energy (i.e. limited BRN) will result in a heterogeneous soil mix material with probably an excessive percentage of unmixed soft soil inclusion in the soil mix matrix. The presence of such inclusions will lead to the decrease of the strength of the soil mix material. Moreover, this heterogeneity will not be compensated using a higher binder content.

On the contrary, the use of an excessive mixing energy will result either in an exaggerated mixing time, by decreasing the penetration/withdrawal velocities which will be deleterious for the time schedule, or in an excessive primary energy (gas oil) consumption, by increasing the rotational speed of the mixing tool.

In 2005, EN 14679 indicated that the rotational speed of the mixing blades is usually 25 (rev/min) to 50 (rev/min) and the blade rotation numbers usually greater than 350 (rev/m). Based on field tests, Topolnicki (2009) correlated the coefficient of variability of the strength of the soil mix material with the BRN and he found that the BRN should exceed the value of 430 (rev/m) to obtain coefficients of variability lower than 0.3 which was acceptable according to his experience. According to Topolnicki and Pandrea (2012), the minimum required BRN depends on the soil type. For cohesive and fine-grained soils (loose sands and clays) about 400 (rev/m) should be achieved to keep the coefficient of variation for the strength within acceptable limits. In non-cohesive and coarse soils slightly lower values can be sufficient.

An equivalent factor was also proposed by Bellato et al. in 2012 for the evaluation of the mixing degree of soil mix material performed with CSM technology: the "Mixing quality parameter", noted μ. Unfortunately, less return on experience is available for that assessment method and, to the best of our knowledge, no specific ranges of values are available in the scientific literature for μ (in function of the soil conditions).

The secret of a good mixing process lies in the mastery of the following plan:

a) Execution of an adapted ground investigation (CPT, drilling, coring…): determination of the nature of the soil and its mechanical properties and chemical analysis (suitability study),

b) Based on the ground investigation and on the design function of the soil mix wall: determination of the design mix (type of binder/cement, binder content, water/binder weight ratio) and of the mixing procedure (mainly the mixing energy, V_p, V_w, R_p, R_w and the execution sequence),

c) After possible field trials, execution of the final soil mix elements with execution monitoring (= production phase),

d) characterization of the final product: i.e., most of the time, the determination of the strength, stiffness and permeability of the soil mix material,

e) Possible geotechnical monitoring of the soil mix wall: monitoring suited to its design functions (e.g. vertical and horizontal displacements controled with laser or total station, inclinometer measurements, determination of the wall deformations by means of optical fibers…).

For the deep mixing contractors, the purpose of this approach will be the implementation of a database (based on the return on experience) useful for future projects. This is therefore not only a question of Quality Assurance/Quality Control (QA/QC).

Concerning the final product of the deep mixing process, i.e. the soil mix material, there are a lot of references available in the literature (see for example Bruce et al., 1998, Porbaha et al., 2000, CDIT, 2002, Kitazume, 2005, Kitazume and Terashi, 2013). For retaining walls in particular, the mechanical characteristics of the soil mix material, its permeability and its adhesion with steel have been investigated with success in the past (see for example Topolnicki, 2004 and Denies et al., 2012). Nevertheless, for permanent applications, the durability of the soil mix material remains a complex topic as there are numerous mechanical, physical and chemical degradation mechanisms observed in practice (see Denies et al. 2020a). To define an obvious design approach for soil mix walls used as retaining structures, it was therefore necessary to clarify the potential design functions of these soil mix walls.

FUNCTIONAL REQUIREMENTS AND DESIGN SPECIFICATIONS

In the handbook, the design and QA/QC requirements depend on the function(s) of the soil mix wall, its lifetime and the risk category of the structure. In Belgium, there are three risk categories: RK1 (low), RK2 and RK3 (high). A distinction is made between the temporary and the permanent soil mix walls. Temporary means that the lifetime of the wall is less than 2 years. Four retaining functions are considered: the temporary earth retaining wall (FUNCTION A), the permanent earth retaining wall (B), the temporary earth-water retaining wall (C) and the earth-water retaining wall with at least one permanent function (D).

The design option related to the **temporary earth retaining wall** (A) is the possibility to consider the interaction between steel and soil mix for the calculations of the bending stiffness and the moment capacity of the wall. For temporary walls, no special measures should be taken, under normal circumstances, regarding the durability of the soil mix material and the corrosion of the steel beam. To avoid leaching (erosion) of the soil mix material, its characteristic UCS (Unconfined Compressive Strength) value noted $f_{sm,k}$ should be at least 0.3 MPa. The value of $f_{sm,k}$ can be computed based on the cumulative frequency curve or using a simplified statistical approach in function of the number of tested in situ cored samples (see handbook for further explanations).

In the presence of aggressive compounds/contaminants in the soil, one should conduct a prior evaluation of the effect of such compounds on the setting reaction and the strength development of the soil mix material. At the same time, the impact of the aggressive compounds on the steel beams should be evaluated. In general, for **permanent retaining walls** (FUNCTION B), the interaction between steel and soil mix will only be considered for the assessment of the bending stiffness of the wall if the soil mix is protected. This interaction should not be taken into account to determine the moment capacity of the soil mix wall. The requirements for the **temporary earth-water retaining wall** (FUNCTION C) are the same than for the FUNCTION A except that the soil mix wall must present a permeability of 10^{-7} m/s and the soil mix material a permeability of 10^{-8} m/s. With a **permanent water retaining function**, if important groundwater flows are present, $f_{sm,k}$ should be larger than 0.5 MPa to resist against internal erosion and leaching.

Temporary and permanent bearing walls (FUNCTIONS E and F) are also considered in the handbook. The forces from the superstructure are uniformly transferred in the soil mix wall. The vertical forces of the underground floors are transmitted via connecting elements between the floor and steel beams. The soil mix elements are preferably reinforced over their entire length. For the transmission of the vertical load to the soil, the adhesion between steel and soil mix is limited by three criteria, as follows:

$$f_{bd} = min\left(0.24\,\eta_2\, f_{sm,k}^{1/2}\ ;\ 10\% f_{sm,d}\ ; 0.30\ MPa\right) \quad [2]$$

In practice, η_2 generally varies between 0.5 and 1 (-). It depends on the beam type and is computed as:

$$\eta_2 = \frac{132 - \sqrt{\frac{4 b_f t_f}{\pi}}}{100} \quad \text{with } \eta_2 \leq 1 \quad [3]$$

b_f is the width of the beam flange and t_f the flange thickness. $f_{sm,d}$ is the design UCS value of the soil mix:

$$f_{sm,d} = \alpha_{sm} \frac{f_{sm,k}}{\gamma_{sm} k_f} \beta \quad [4]$$

where, α_{sm}, the long-term factor is equal to 1 (-) for temporary and 0.85 (-) for permanent walls. γ_{sm} is the material factor equal to 1.5 in Belgium. k_f is a factor taking into account the way the UCS is determined: if the UCS is determined based on samples from the in situ walls, k_f is equal to 1.0 (-); in all other cases, e.g. starting from 'estimated' values, this factor is equal to 1.1 (-). β is a correction factor for the young age of the soil mix material; depending on various factors, β = 0.3 to 0.7 after 7 hardening days and β = 0.6 to 0.8 after 14 hardening days. β is used in case of excavation a few days after the execution of the soil mix.
For **permanent bearing walls (F)**, the adhesion, f_{bd}, can only be considered, in absence of contaminants into the ground, if $f_{sm,k}$ is larger than 3 MPa, if the wall is protected against frost and is not directly exposed to the ambient air and if special measures are taken to protect the beam against corrosion (EN 1993-1-1).

For **permanent retaining and bearing walls**, exposure of soil mix material to ambient air (especially in ventilated zones) and to freeze-thaw cycles should be prevented in order to avoid evaporation shrinkage and progressive shedding of the soil mix resulting in a decrease in strength and stiffness over time. For permanent applications, it is therefore required that the soil mix wall is protected by a protection wall/barrier (reinforced concrete wall, shotcrete or specific coating...). Furthermore, the following aspects must be considered: the creep behavior, the durability aspects of the soil mix material, the wall settlements and, if relevant, the effect of contaminated soils and the potential seismic and dynamic loads. According to the handbook, it is recommended to not consider the soil mix material in itself as a corrosion protective measure and to take different protection measures, as described in EN 1993-5 (EC3-5). Finally, long-term reduction factors are applied to the strength (with the factor α_{sm} of 0.85) and stiffness (divided by 2) of the soil mix.

Temporary and permanent cut-off walls (FUNCTIONS G and H) are also considered in the handbook.

DESIGN OF THE SOIL MIX WALLS

In Belgium, geotechnical design falls under the auspices of Eurocode 7, EC7 (EN 1997-1), and its National Annex. Design of a retaining structure consists of verifying the stability and deformations. Every failure mechanism must be calculated based on its ultimate limit state (ULS) and its serviceability limit state (SLS). Spring models, finite elements or finite difference methods may be used for the wall calculations. Figure 26 provides a flow chart for the design of a soil mix wall used as retaining wall. If some design aspects are similar to the design considerations of other retaining walls (concrete secant pile walls, sheet pile walls…), the handbook provides design specifications adapted to the properties of the soil mix material. Beyond the determination of the design values characterizing the strength parameters of the soil mix, the designer will particularly concentrate on the three following aspects:

- the verification of the arching effect,
- the assessment of the effective bending stiffness of the soil mix wall (composite steel-soil mix section),
- the structural design of the soil mix wall (including the moment capacity of the composite section).

Fig. 26. Flow chart for the design of a soil mix wall used as retaining wall (according to the handbook) – "H", in the figure, means BBRI/SBRCURnet Handbook Soil mix walls (2018)

The following paragraphs briefly discuss the main principles of these design stages, only valid for soil mix elements reinforced with steel beams (reinforcement cages are not considered in the handbook).

Verification of the arching effect

It must be verified that the earth and water pressures are transmitted to the steel beams via a pressure arch (cf. Fig. 19). According to Eurocode 2, EC2 (EN 1992-1-1), to ensure the arching effect, the distance between the steel beams must be limited as follows:

$$l_s < 3H \qquad [5]$$

where l_s is the distance between the steel beams (axis-to-axis) and H the maximal height available for the development of the arch in the soil mix material (see Fig. 19). After this first verification, the designer focuses on the geometry of the pressure arch, i.e. on the geometrical/analytical determination of:
- the height of the pressure arch (noted z in Fig. 19),
- the angle α at the location of the base of the arch (illustrated in Fig. 19),
- the thickness of the pressure arch (d_{bg}) at the location of the beam and in the middle of the arch ($d_{bg;mid}$).
The geometry of the pressure arch is determined with an iterative calculation varying α by assuming a parabolic function for the central line of the arch, i.e. the red line in Fig. 19 (see handbook for more details). Finally, the stresses developing in the soil mix arch are verified based on a 'strut and tie' model given in Fig. 27. The maximum compressive stresses at the connection with the beam and in the middle of the arch are assessed and compared with the admissible stresses based on the material resistance and EC 2 rules:

$$\sigma'_{arch,base} = \frac{N'_{base}}{d_{bg}} = \frac{0.5\,\sigma_{hor}(l_s - b_f - 2c_1)}{(b_f \sin\alpha)\sin\alpha} < k_2\,\nu'\,f_{sm,d} = 0.85\left(1 - \frac{f_{sm,k}}{250}\right) f_{sm,d} \quad \text{in [MPa]} \qquad [6]$$

$$\sigma'_{arch,mid,max} = 2\,\sigma'_{arch,mid,av} < 0.6\,\nu'\,f_{sm,d} = 0.6\left(1 - \frac{f_{sm,k}}{250}\right) f_{sm,d} \quad \text{in [MPa]} \qquad [7]$$

$$\text{with } \sigma'_{arch,mid,av} = \frac{N'_{middle}}{d_{bg;mid}} = \frac{\sqrt{N'^2_{base} - V^2_{mid}}}{b_f \tan\alpha} = \frac{\sqrt{\left(\left(\frac{0.5\sigma_{hor}(l_s - b_f - 2c_1)}{\sin\alpha}\right)^2 - (0.25\,l_s\,\sigma_{hor})^2\right)}}{b_f \tan\alpha} \qquad [8]$$

V_{mid} is the shear force at the bend of the arch in the strut and tie model. c_1 is the beam cover (see Fig. 27). The maximum shear stress in the cross-section of the arch is also compared with the material resistance:

$$\tau_{Ed} = \frac{3}{2}\frac{V_{mid}}{d_{bg;mid}} = \frac{3}{2}\frac{0.25\,l_s\,\sigma_{hor}}{b_f \tan\alpha} < f_{sm,td} + \frac{15}{100}\sigma'_{arch,mid,av} = \alpha_{sm}\frac{0.21 f_{sm,k}^{2/3}}{\gamma_{sm} k_f}\beta + \frac{15}{100}\sigma'_{arch,mid,av} \qquad [9]$$

where $f_{sm,td}$ is the design value of the tensile strength of the material. According to EC 2, the increase of the shear strength with 15% of $\sigma'_{arch,mid,av}$ is admitted if $\sigma'_{arch,mid,av}$ is smaller than 0.2 $f_{sm,d}$.

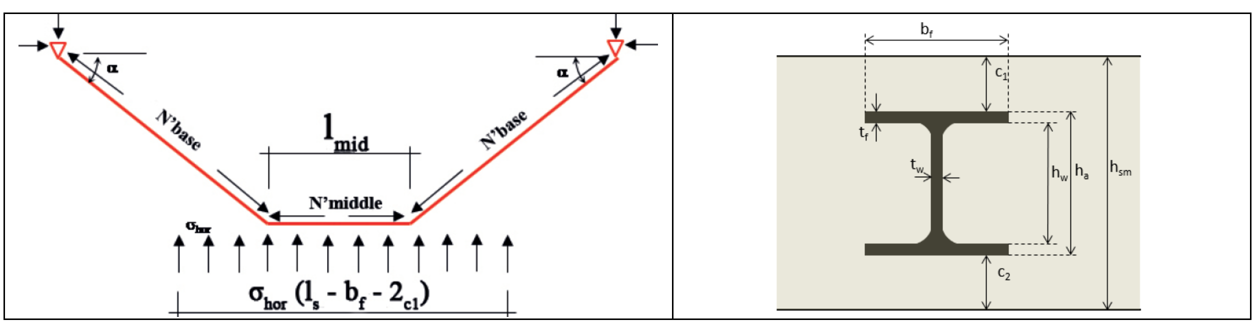

Fig. 27. Model for the verification of the arching effect in the soil mix (left) and notations (right)

Detailed examples of analytical and numerical (FEM) computations are given for the verification of the arch in Denies et al. (2020b and c), respectively for soil mix walls made with panels and columns.

If the development of such pressure arch in the soil mix material can easily be verified for continuous wall segment, it is more difficult to model it in the corner of an excavation (see Fig. 28). In case of a continuous wall, both sides of the web of the beam are taken between similar pressure arches. This results in an equilibrium of forces. With a corner solution this is not the case.

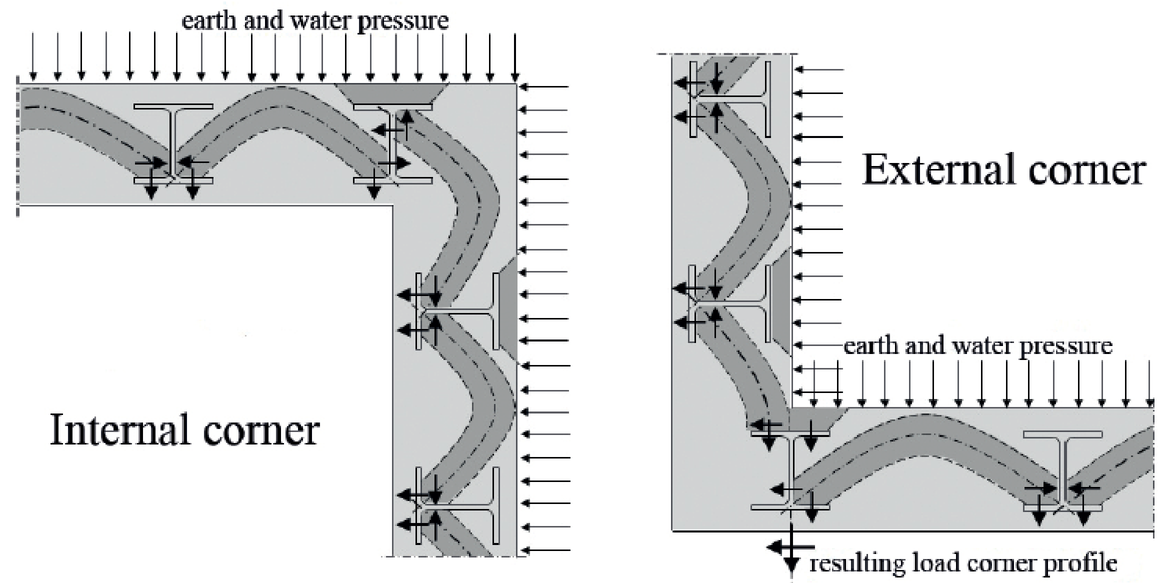

Fig. 28. Possible pressure arches in the corner and affecting loads from the pressure arches at the location of an internal and external corners (source: handbook)

Such aspect is broached in the handbook which proposes constructive solutions to reinforce the corners of the excavations (see Fig. 29 for example).

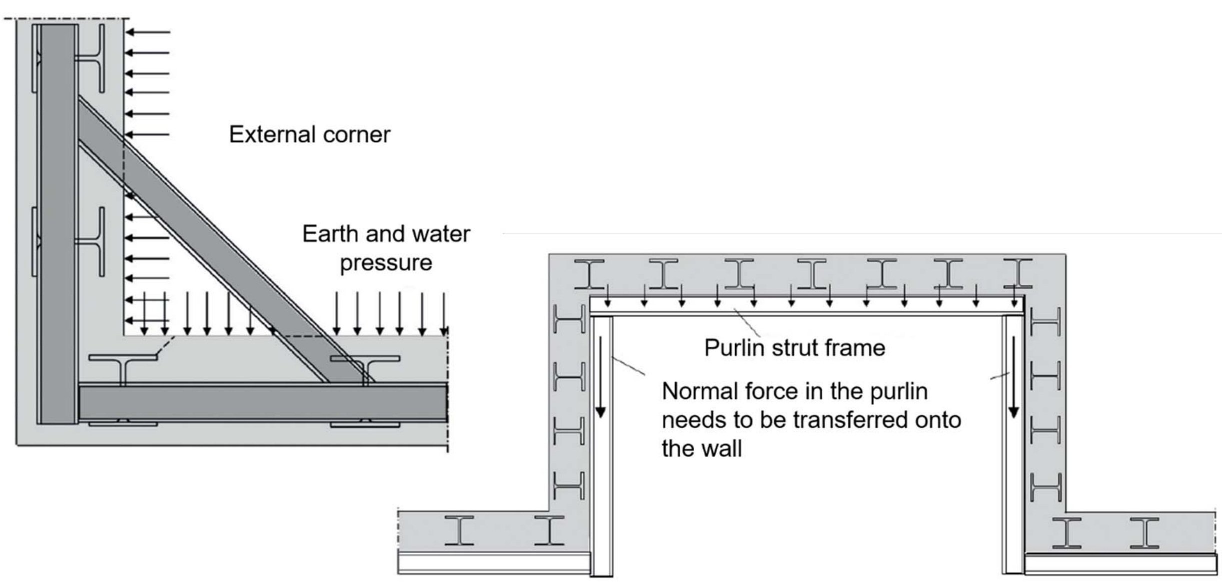

Fig. 29. Welded steel frame on the top of the wall at the location of an external corner (left) and principle of the transfer of load from the strut frame onto the cross-wall (right)

Assessment of the horizontal bending stiffness of the soil mix wall

A crucial point in the design of the retaining wall is the assessment of its bending stiffness, EI. In practice, the designers introduce the value of the bending stiffness of the wall in their computational program for the purpose of assessing the bending moments and horizontal displacement. It is therefore important to apply a representative value of the bending stiffness. In the present design approach, two methods are proposed for the computation of the bending stiffness of the composite section 'steel-soil mix'.

The first method is the most appropriate to make a realistic assessment of the bending stiffness of the cracked soil mix wall. Based on EC2, the effective bending stiffness is the average of the uncracked stiffness EI_1 and the cracked stiffness EI_2:

$$EI_{eff} = \frac{EI_1 + EI_2}{2} \qquad [10]$$

The height of the compressed zone in the calculations of the cracked stiffness is determined considering a plastic stress distribution (see handbook for details).

The second method consists in a simplified approach. The composite stiffness is determined as the sum of the stiffness of the reinforcement and the stiffness of the soil mix section in compression assuming that the neutral line goes through the middle of the steel beam. The effective bending stiffness is calculated as:

$$EI_{eff} = E_a I_a + E_{sm} \left[\frac{b_{c1} \left(\frac{h_{sm}}{2} \right)^3}{3} \right] \qquad [11]$$

where $E_a I_a$ is the bending stiffness of the steel beam, E_{sm} the modulus of elasticity of the soil mix material, h_{SM} the thickness of the soil mix wall (see Fig. 27) and b_{c1} the effective width for the bending stiffness:

$$b_{c1} = \frac{L}{4} \qquad [12]$$

where L is the distance between two zero moment points along the wall. Moreover, b_{c1} is limited to the distance between the two steel beams: $b_{c1} < l_s$. In practice, it is to note that b_{c1} is generally equal to l_s.

Above formulas [10] and [11] give the bending stiffness per effective width. These values can be converted into bending stiffness per meter of wall dividing the computed values of EI_{eff} by the effective width b_{c1}.
The simplified method (equation 11) gives bending stiffness values that are approximately 10 to 20% lower than those calculated with the more detailed calculation method (equation 10).
The characteristic value of E_{sm} can be taken as the average value of the results of the tests for its determination. This average value must be consistent with the obtained UCS values of the soil mix material regarding the existing correlations between both parameters (see Denies et al., 2012).
Using equations [10] and/or [11] for the assessment of a composite bending stiffness, the realization of calculations in two phases with, respectively, a 'high' and 'low' estimated E_{sm} value, is of little use in most cases. An approach with high or low E_{sm} may only be useful for walls with multiple supports and in case of important wall displacements. With multiple-supported (hyper-static) walls, the bending stiffness will have a larger effect on the internal forces than with unanchored or single anchored/braced walls.
Different verifications can possibly be performed at different depths in function of the potential variation of the modulus of elasticity of the soil mix material with depth. In this case, the wall will be fragmented into multiple parts in depth with different bending stiffness values.
For permanent applications, the composite stiffness will be considered only if the wall is protected and the value of E_{sm} will be divided by 2 due to the potential creep behavior of the soil mix material.

Structural design of the soil mix wall – determination of its structural strength

In the past, the designers only considered the resistance of the steel beam for the assessment of the forces in the soil mix wall (normal forces, shear forces and moments). Nevertheless, as shown by the results of the seventeen large-scale bending tests performed on real soil mix elements by the BBRI, the soil mix material also contributes to the structural resistance of the soil mix wall. For the **calculation of the moment capacity**, some values must first be determined: the soil mix resistance, the effective width for the structural verification, b_{c2}, and any potential uncertainty factors on the geometry or regarding long-term effects.
For the structural verification of soil mix walls made of panels, the effective width is initially limited to:

$b_{c2} = \frac{L}{4}$ and $b_{c2} < l_s$ for soil mix panels [13]

For the walls made of columns, the calculation of the moment capacity is based on the reinforced columns. Non-reinforced columns are ignored. b_{c2} is then set equal to the axis-to-axis distance of the columns, d_2:

$b_{c2} = d_2$ for soil-cement columns [14]

In order to allow the two materials to work together, shearing forces should be transferred between the steel beam and the soil mix material. The maximum value of the adhesion is given by equation [2]. The greater the effective width, the greater the shear strength that must be transferred. By equalizing the compressive strength of the compressed soil mix section and the one-sided adhesion between the beam and the soil mix on the surface (b_f L_{ss}), the following boundary value b_{c2} can be derived for the zone in compression:

$$b_{c2} = \frac{b_f L_{ss} f_{bd}}{c_1 f_{sm,d}} \qquad [15]$$

where c_1 is the cover above the beam (see Fig. 27), computed as $c_1 = (h_{sm} – h_a – 2.e)/2$ with e the eccentricity of the beam towards the compressed side. L_{ss} is the length over which the shear strength should be spread; i.e. the distance from the maximum moment to the zero moment point, approximate to L/2. The unreinforced part, at the bottom of the soil mix wall, is not considered.
Finally, in order to limit the effective compressive zone in case of medium and small beams, especially in combination with limited compressive strength, the effective width is (alongside the three previous criteria [13] to [15]) limited to 2 times the flange width, b_f. With this extra rule, a too optimistic calculation is avoided in case of large axis-to-axis distance of the beams or large distances between the zero moment points. Moreover, the moment capacity of walls made of panels and columns are also closer to each other.

For **permanent** situations, the interaction between steel and soil mix is not considered to determine the moment capacity of the soil mix wall which is taken equal to the moment capacity of the steel beams only. According to Eurocode 3, EC3 (EN 1993-1-1), this moment capacity can be calculated in two ways: elastic or plastic. Four classes of cross-sections are defined in EC3 depending on the width to thickness ratio of the parts subject to compression (cf. Table 5.2 of EC3). In agreement with EC3, a beam can be plastically calculated if it belongs to beam class 1 or 2 when it is subject to bending stress. Most beams that are used for soil mix walls comply with this. Exceptions include the "class 3" beams HEA260/280/300 of S355 steel quality. Beams that belong to class 3 must be calculated elastically. For several beams, the use of a reduced steel section (as corrosion protection measure) may result in an increase of class. Considering the beams most often used for soil mix walls, the gain on the moment capacity by calculating plastically instead of elastically is approximately 10 to 14%. For combined bending the regulations of EC3 apply.

For **temporary** walls, the interaction between steel and soil mix can be considered to determine the moment capacity of the composite section, as proposed in Eurocode 4, EC4 (EN 1994-1-1). The methods specified in EC4 are plastic methods and may only be applied for beams of class 1 or 2. The resistance of a composite section to combined compression and bending may be calculated assuming rectangular stress blocks and taking account of the design shear force. The tensile strength of the soil mix material should be neglected. The yield strength of the steel f_y may not be greater than 460 MPa. The present method considers the limitation for the adhesion between steel and soil mix given by eq. [2]. Based on a centrally placed steel beam (i.e. with $c_1 = c_2$ in Fig. 27), the design interaction curve (M-N) can be deduced in this symmetric situation in accordance with EC4 (§6.7.3.2). This design interaction curve can be calculated by using available software. A simplified method, replacing the curve by a polygonal diagram, is also given in EC4.

The handbook presents design tables and charts providing values for the moment capacity of the composite section. For example, Table 1 and Fig. 30 give the moment capacities for a temporary CSM panel reinforced with IPE beams. M(Rd,a,el) and M(Rd,a,pl) are the moment capacities computed, only considering the moment capacity of the steel beam, respectively with an elastic or a plastic method: W_{el} and W_{pl} (as given in the product catalogues of the beams). M(Rd, 2 MPa) is the moment capacity considering a contribution of the soil mix material (with $f_{sm,k}$ = 2 MPa). The design values of the moment capacities, given in Table 1, are applicable per axis-to-axis distance between the beams. These values need to be divided by l_s to obtain the moment capacity per metre of wall. The color of the cells gives an indication of the determining factor for the moment capacity. Moment capacities of the yellow cells are limited by the second adhesion criterion ($f_{bd} \leq 10\% f_{sm,d}$). The blue cell values are limited by the third criterion ($f_{bd} \leq 0.3$ MPa). Other moment capacities are governed by geometric limitations for b_{c2}. The contribution of the soil mix material results in a reduction of the stress in the steel beams. Without eccentricity of the steel beam, the bending moments obtained are 113 to 138% higher than those obtained with an elastic method only considering the moment capacity of the steel beams. With an eccentricity of 5 cm, this increase still ranges between 113 and 135%.

For the **calculation of the shear resistance**, one may refer to EC3. The shear force, V_{Ed}, should be fully absorbed by the web of the steel beam, with preferably:

$$V_{Ed} < 0.5\, V_{pl,Rd} \quad [16]$$

with:

$$V_{pl,Rd} = \frac{A_v f_{yd}}{\sqrt{3}} \quad [17]$$

where A_v is the active plastic shear surface which can be found in the product information of the rolled beams or in EC3 (§6.2.6). The influence of transverse shear forces on the resistance to bending and normal force should be considered when determining the interaction curve, if the shear force V_{Ed} exceeds 50% of the design shear resistance of the steel section, $V_{pl,Rd}$. The influence of the vertical shear on the resistance to bending may be taken into account by reducing the web thickness or the steel strength $(1 - \rho)\, f_{yd}$ where:

$$\rho = \left(2\frac{V_{Ed}}{V_{Rd}} - 1\right)^2 \quad [18]$$

In any case, the shear force, V_{Ed}, should not exceed the shear resistance of the steel section, $V_{pl,Rd}$.

Vertical loads can affect the soil mix wall due to load transfer on the top of the wall, through intermediate floors and the base plate or through the vertical component of anchor forces or strut forces. The verification of the **strength of the soil mix wall against vertical loads** involves two aspects:
- the vertical stress on the soil mix material and reinforcement must be limited to the admissible values, and that in combination with the acting bending moments and shear forces;
- one must verify whether there is enough adhesion to avoid any debonding or punching of the beams under the effect of the vertical loads.

Table 1. Moment capacity of a CSM panel (55 cm thickness) reinforced with IPE beams (S235)

Axis-to-axis reinforcement: l_s = 1.10 m, distance between two zero moment points along the wall: L = 5 m

$f_{sm,k}$ = 2, 4 and 6 MPa, α_{sm} = 1, β = 1, γ_{sm} = 1.5, safety coefficient for steel γ_{M0} = 1 (-)

The moment capacities (kNm) are applicable per axis-to axis distance between the beams, ls

	IPE200	IPE220	IPE240	IPE270	IPE300	IPE330	IPE360	IPE400	IPE450
Eccentricity of the steel beam: e = 0									
M(Rd,a,el)	45.7 100%	59.2 100%	76.2 100%	100.8 100%	130.9 100%	167.6 100%	212.3 100%	271.7 100%	352.5 100%
M(Rd,a,pl)	51.8 114%	67.1 113%	86.2 113%	113.7 113%	147.7 113%	189.0 113%	239.5 113%	307.1 113%	400.0 113%
M(Rd,2)	56.0 123%	72.0 122%	90.3 118%	119.2 118%	155.0 118%	193.6 116%	244.1 115%	307.2 113%	400.0 113%
M(Rd,4)	61.9 135%	78.7 133%	97.9 128%	128.4 127%	165.9 127%	205.2 122%	256.5 121%	320.3 118%	412.8 117%
M(Rd,6)	63.2 138%	80.2 135%	99.6 131%	130.4 129%	168.3 129%	210.7 126%	266.2 125%	331.2 122%	424.4 120%
Eccentricity of the steel beam: e = 5 cm									
M(Rd,a,el)	45.7 100%	59.2 100%	76.2 100%	100.8 100%	130.9 100%	167.6 100%	212.3 100%	271.7 100%	352.5 100%
M(Rd,a,pl)	51.8 114%	67.1 113%	86.2 113%	113.7 113%	147.7 113%	189.0 113%	239.5 113%	307.1 113%	400.0 113%
M(Rd,2)	55.4 121%	70.9 120%	88.6 116%	116.4 115%	150.5 115%	189.0 113%	239.5 113%	307.1 113%	400.0 113%
M(Rd,4)	60.5 132%	76.5 129%	94.6 124%	123.0 122%	157.8 121%	196.7 117%	247.3 116%	310.7 114%	402.5 114%
M(Rd,6)	61.6 135%	78.6 133%	98.1 129%	128.5 128%	163.9 125%	203.0 121%	254.1 120%	317.9 117%	410.3 116%

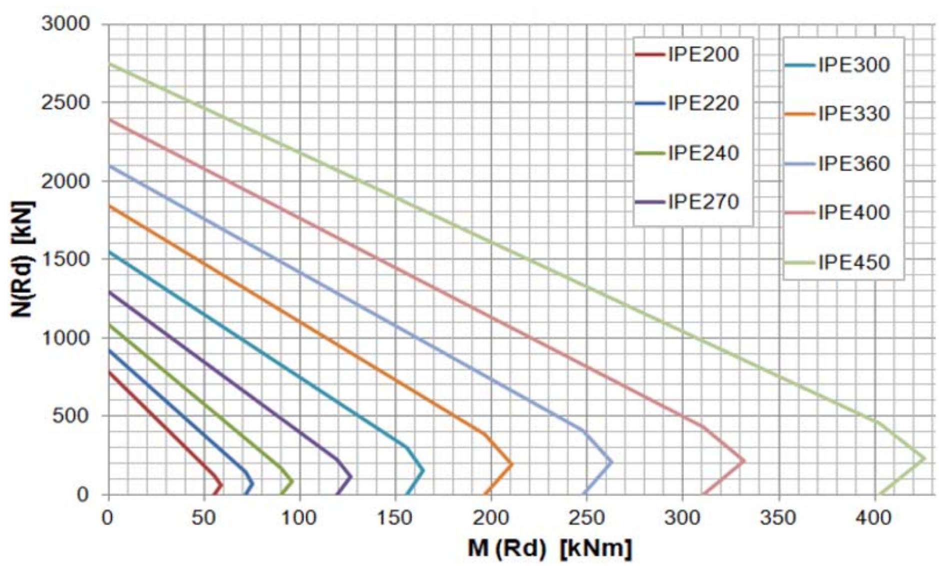

Fig. 30. Simplified interaction diagram for a CSM panel (55 cm thickness) with IPE beams (S235)

Particular aspects related to the resistance of the soil mix against punching in the zone of the anchor is described in the handbook. In function of the horizontal support solution designed by the engineer, the contact stress directly underneath the anchor plate or the steel beam will be verified regarding the compressive strength of the soil mix material.

The additional compressive stress (represented in Fig. 31) developing between the anchor plate/support beam and the steel beams, ensuring the bending resistance of the wall, will also be analyzed and compared to the compressive strength of the soil mix material.

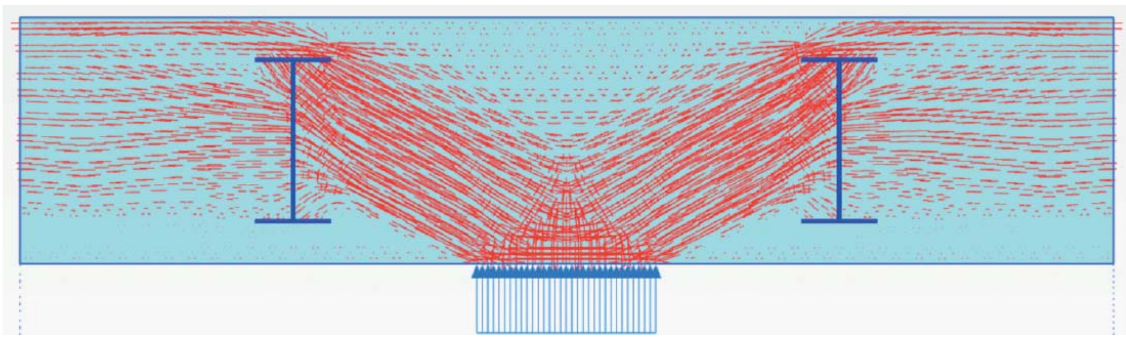

Fig. 31. FEM representation of the stress trajectories/paths at the level of the anchor plate/seat

Finally, the resistance of the soil mix material against punching failure will be regarded defining a punching failure cone in the wall (see Fig. 32) and verifying that the shear stress developing along the failure cone surface remains smaller than the shear strength of the soil mix material.

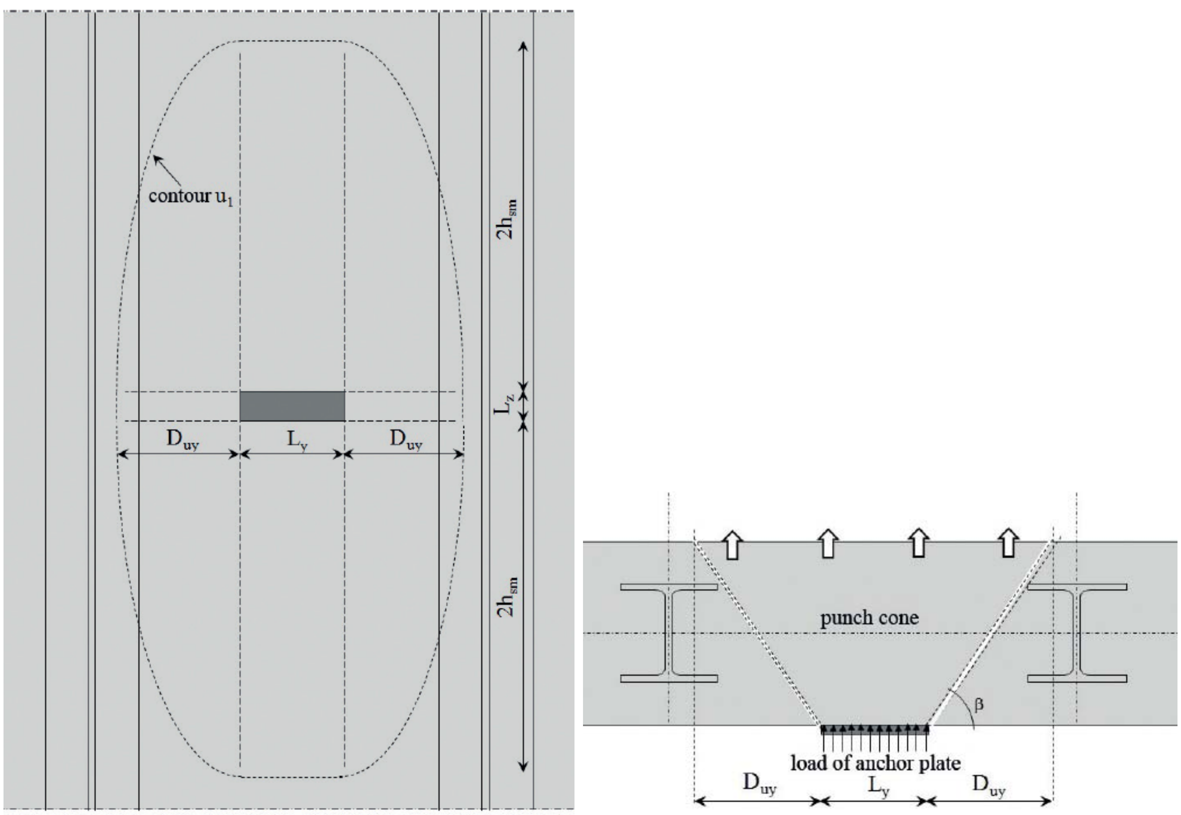

Fig. 32. Shape (left) and perimeter (right) of the punching failure cone

CONCLUSIONS AND PERSPECTIVES

The present keynote deals with the execution of soil mix walls for the construction of retaining structures. Constructive aspects are first presented. Then, some specific design aspects proposed in the BBRI/SBRCURnet Handbook Soil mix walls (2018) are discussed. Requirements are given for the different functions of the soil mix walls (retaining, bearing and cut-off) and regarding their lifetime (temporary or permanent). A design flow chart is proposed summarizing the different aspects which must be taken into account by the designer. The principle of the soil mix wall used as retaining structure is highlighted considering the arching effect developing in the soil mix material. The geometry of the pressure arch is verified and the stresses arising in this arch are compared with the admissible stresses based on the material resistance. Methods are then proposed for the computation of the composite bending stiffness of the soil mix wall. Finally, one concentrates on the contribution of the soil mix material to the moment capacity of temporary walls. To illustrate the method, a design table is given for a CSM panel reinforced with IPE steel beams. In general, the contribution of the soil mix material to the structural resistance of the soil mix wall results in a decrease of the stress in the steel beams. Considering the tables proposed in the handbook for different configurations of soil mix walls (panels and columns reinforced with IPE or HEA beams), the admissible reduction of the steel section is ranging between 10 to 38%. The design approach of the handbook agrees with the principles of the Eurocodes. It allows to design a soil mix wall for a retaining structure taking into account the nature of the in situ produced soil mix material, its heterogeneity, its durability, the functions and the lifetime of the retaining wall and the risks related to the project. The aim of the present keynote, including a lot of formulae, is not to serve directly as guidelines for the verification of the soil mix walls but, rather, to illustrate several aspects of the design approach proposed in the handbook. The use of equations and criteria often helps the geotechnical engineers to better understand design principles.

If large advances have been performed in this application of the deep mixing technology, areas for further researches and developments still remain. For example:
- the influence of the deep mixing equipment on the final product (which is certainly a tricky topic),
- the minimal mixing energy to be used during execution to obtain homogeneous soil mix material (in function of the soil type),
- the durability of the soil mix material (notably if it is used in polluted soils),
- the improvement of our knowledge and mastery of the cement technology to improve this durability (cf. Denies et al. 2020a),
- the identification of chemicals possibly present in the soil influencing the setting reactions, the hardening process and the durability of the soil mix material,
- the alkaline-character of the soil mix material (and its evolution with time) and its potential ability to protect steel reinforcements against corrosion,
- the ways to protect the soil mix wall against frost, carbonation and wet/dry cycles if the wall is exposed to the ambient air,
- as the high porosity of the soil mix material (which decreases its resistance and durability) results from the high water/binder ratio used for the execution, practical research on potential additives, such as superplasticizers adapted to the soil mix technology is an interesting trail for the practice,
- the behavior of the soil mix wall in case of fire,
- the bearing capacity of the soil mix elements used as alternative to pile foundation or as rigid inclusion,
- the tensile behavior of the soil mix elements,
- the use of reinforcement cages in place of beams (in particular the development of a reliable design approach for retaining structures),
- the development of design methods in agreement with the Eurocodes for other fields of applications of the technique (e.g. global mass stabilization and reinforcement of land levees),

Further research actions are thus needed to improve our understanding of the behavior of the "reinforced" soil mix material particularly in those new fields of applications.

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REFERENCES

BBRI/SBRCURnet. 2018. Handbook Soil mix walls. Taylor and Francis Group, ISBN 978 90 5367 641 7.

Bellato, D., Dalle Coste, A., Gerressen, F.-W. and Simonini, P. 2012. Long-term performance of CSM walls in slightly overconsolidated clays. International symposium of ISSMGE - TC211. Recent research, advances & execution aspects of ground improvement works. 31 May-1 June 2012, Brussels, Belgium, Vol. III, pp. 23-32.

Bruce, D.A., Bruce, M.E.C., DiMillio, A.F. 1998. Deep mixing method: a global perspective. Soil Improvement for big digs, Boston (Massachusetts, USA), October 18-21, 1998, ASCE, Geotechnical special publication 81: 1-26.

CDIT - Coastal Development Institute of Technology. 2002. The Deep Mixing Method – Principle, Design and Construction. A. A. Balkema Publishers Lisse/Abingdon/Exton (PA)/Tokyo.

CUR 166. 2012. Damwandconstructies. ISBN 90 3760 063 8 [in Dutch].

Denies, N., Huybrechts, N., De Cock, F., Lameire, B., Vervoort, A., Van Lysebetten, G. and Maertens, J. 2012. Soil Mix walls as retaining structures - mechanical characterization. IS-GI Brussels, vol. III, 99-115.

Denies, N., Van Lysebetten, G., Huybrechts, N., De Cock, F., Lameire, B., Maertens, J. and Vervoort, A. 2014. Real-Scale Tests on Soil Mix Elements. DFI-EFFC Conference, Stockholm, 647-656.

Denies, N., Huybrechts, N., De Cock, F., Lameire, B., Maertens, J. and Vervoort, A. 2015. Large-scale bending tests on soil mix elements. IFCEE, San Antonio, 2394-2409.

Denies, N., Huybrechts, N., Kouamé, J.-C., Laurent, G., Eggermont, T. and Bottiau, M. 2020a. Thoughts on the design mix for soil mix walls used as permanent retaining structures. Proceedings of the DFI Deep Mixing conference, June 15-18, 2020.Gdansk.

Denies, N., Allani, M., Huybrechts, N., Kouamé, J.-C., Laurent, G., Eggermont, T. and Bottiau, M. 2020b. Finite element modeling of the arching effect in retaining walls made of soil mix panels. Proceedings of the DFI Deep Mixing conference, June 15-18, 2020.Gdansk.

Denies, N., Allani, M., Huybrechts, N., Kouamé, J.-C., Laurent, G., Eggermont, T. and Bottiau, M. 2020c. Finite element modeling of the arching effect in retaining walls made of soil-cement columns. Proceedings of the DFI Deep Mixing conference, June 15-18, 2020.Gdansk.

EN 14679 – 2005. Execution of special geotechnical works - Deep mixing. European Standard.

EN 1992-1-1: 2004. Eurocode 2: Design of concrete structures.

EN 1993-1-1 – 2005. Eurocode 3: Design of steel structures.

EN 1993-5 – 2007. Eurocode 3 - Design of steel structures - Part 5: Piling.

EN 1994-1-1, 2005. Eurocode 4: Design of composite steel and concrete structures.

EN 1997-1 – 2004. Eurocode 7 - Geotechnical design - Part 1: General rules.

Kitazume, M. 2005. State of Practice Report – Field and laboratory investigations, properties of binders and stabilized soil. International Conference on Deep Mixing, Stockholm (Sweden), 23-25 May 2005, Vol. 2, 660-684.

Kitazume, M. and Terashi, M. 2013. The Deep Mixing Method. CRC Press/Balkema. Taylor and Francis Group, London.

Porbaha, A., Shibuya, S. and Kishida, T. 2000. State of the art in deep mixing technology. Part III: geomaterial characterization. Ground Improvement (2000) 3: 91-110.

Topolnicki, M. 2004. In situ soil mixing. Book chapter in M.P. Moseley, K. Kirsch (Eds.), Ground Improvement, 2nd ed., Spon Press. ISBN 0-415-27455-9.

Topolnicki, M. 2009. Design and execution practice of wet Soil Mixing in Poland. International Symposium on Deep Mixing & Admixture Stabilization, Okinawa, 19-21 May, 2009, pp. 195-202.

Topolnicki, M. and Pandrea, P. 2012. Design of in-situ soil mixing. International symposium of ISSMGE - TC211. Recent research, advances & execution aspects of ground improvement works. 31 May-1 June 2012, Brussels, Belgium.