Deep Soil Mix technology in Belgium: Effect of inclusions on design properties

Patrick Ganne[1], Nicolas Denies[2], Noël Huybrechts[3], André Vervoort[4], Abbass Tavallali[5], Jan Maertens[6], Bart Lameire[7] and Flor De Cock[8]

[1,2,3] Belgian Building Research Institute, Avenue P. Holoffe 21, B-1342 Limelette, Belgium; nde@bbri.be

[4,5] Katholieke Universiteit Leuven, Kasteelpark Arenberg 40, B-3001 Leuven, Belgium; Andre.Vervoort@bwk.kuleuven.be

[6] Jan Maertens bvba & Katholieke Universiteit Leuven, Kasteelpark Arenberg 40, B-3001 Leuven, Belgium; Jan.Maertens.bvba@skynet.be

[7] Belgian Association of Foundation Contractors ABEF, Pieter Cuypersstraat 3, B-1040 Brussel; Bart@lameireft.be

[8] Geotechnical Expert Office Geo.be, Hunselveldweg 33, B-1750 Lennik; fdc.geobe@skynet.be

ABSTRACT

The application of deep soil mix (DSM) technology in Belgium is sharply increasing. Next to soil improvement applications, DSM walls are extensively used for excavation support. Even permanent retaining and foundation applications with soil mix are increasingly applied. This paper gives an overview of the DSM procedures carried out in Belgium and deals with methodologies applied to determine the amount of soil inclusions, the elastic modulus and the compressive strength of DSM material. The influence of soil inclusions on the stiffness of DSM material is investigated with the help of numerical simulations. The methodologies are validated on a large population of laboratory tests on in situ DSM material, executed in Belgian soils. These research activities have been performed in the framework of the research program "Soil Mix" that the Belgian Building Research Institute (BBRI) carries out in collaboration with the Catholic University of Leuven and the Belgian Association of Foundation Contractors (ABEF). This research program is financially supported by the Agency for Innovation by Science and Technology of the Flemish Region IWT (BBRI, 2009-2013).

DEEP MIX SYSTEMS IN BELGIUM

The CVR C-mix®, the TSM and the CSM are the three most used types of DSM systems in Belgium. All three are wet deep mixing systems.

CVR C-mix®

The CVR C-mix® is performed with an adapted bored pile rig and a special designed shaft and mixing tool. This tool rotates around a vertical axis at about 100 rpm and cuts the soil mechanically. Simultaneously, the water\binder mixture (w\b weight ratio between 0.6 and 0.8), is injected at low pressure (< 5 bar). The injected quantity of binder amounts mostly to 350 and 450 kg binder/m³, depending on the soil conditions. The binder partly (between 0% and 30%) returns to the surface. This is called 'spoil return'.

The resulting DSM elements are cylindrical columns with diameter corresponding to the mixing tool diameter, varying between 0.43 and 1.03 m. When deep soil mix is used as a retaining structure, the production rate is about 160 m² of DSM wall per day (single 8 hrs shift).

In order to increase the production rate, a CVR Twinmix® and a CVR Triple C-MIX® can be used. A twinmix has two mixing tools, mixing two overlapping cylindrical columns (total wall element length of 0.8 to 1.2 m) at the same time. The daily production increases till 210 m². A CVR Triple C-mix® has three mixing tools in line, with a total wall element length of 1.5 to 1.8 m. The production rate increases to 300 m² per day.

Tubular Soil Mix (TSM)

The TSM technique uses a mechanical and a hydraulic way of mixing. Apart from the rotating (around the vertical axis) mixing tool, the soil is cut by the high pressure injection (till 500 bar) of the water\binder mixture with w\b chosen between 0.6 and 1.2. The injected quantity of binder mixture amounts mostly to 200 and 450 kg binder/m³, depending on the soil conditions. Part of the binder (between 0% and 30%) returns to the surface as spoil return.

The resulting DSM elements are cylindrical columns with a diameter between 0.38 and 0.73 m. The production rate is about 80 m² of DSM wall per day.

Again, a twin and a triple version exist. The total wall length of the two (three) cylindrical columns of a twin (triple), varies between 0.8 and 1.4 m (1.2 and 2.1 m). In this way, the production rate is increased till about 180 (twin) and 250 m² (triple) of DSM wall per day.

Cutter Soil Mix (CSM)

A CSM device is commercially available. It makes use of two cutting wheels that rotate independently around a horizontal axis, cutting the soil. At the same time, the water\binder mixture is injected at low pressure (< 5 bar) with w\b ratio chosen between 0.6 and 1.2. The injected quantity of binder amounts mostly to 200 and 400 kg binder/m³, depending on the soil conditions. Part of the binder (between 0% and 30%) returns to the surface as spoil return.

The resulting DSM elements are rectangular panels. In Belgium, these panels have mostly a length of 2.4 m and a thickness of 0.55 m, though cutter devices with other dimensions are available. The production rate is about 100 m² to 250 m² per day.

DESCRIPTION OF INCLUSIONS IN DEEP MIXED MATERIAL

Due to the specific procedure of deep mixing, soil inclusions are inevitable. In this paper, all inclusions in DSM material are considered as soft soil inclusions. The volume of soil inclusions of in situ executed deep mix should be quantified in order to study its influence on the material strength.

Two methodologies to take into account soil inclusions are presented and illustrated with case studies of DSM material executed in several Belgian soils (quaternary and tertiary sands, silt, alluvial clay and stiff clay).

Description of the methodologies

In order to quantify the volume of soil inclusions, in situ executed DSM columns and panels are observed. Soil inclusions can be described based on entire sections of DSM columns/panels as well as on drilled cores.

The two methodologies are the surface percentage (A) and the line percentage (B).

(A) The calculation of the surface percentage of soil inclusions involves five processing steps:

1. DSM columns or panels are executed in situ by standard DSM procedure.
2. The test columns/panels are (partly) excavated; the column/panel should be sawn to create a statistically representative ‘fresh’ saw-cut section. Alternatively, the saw-cut of a core drill can also be used.
3. The saw-cut surface is photo-graphically digitized to recompose one digital mosaic photo. The pixel resolution is about 0.3 mm.
4. Using commercially available image processing techniques (IPT), soil inclusions are assigned in black on the digital mosaic photo. As the soil inclusions are not always observable, manual verifications are performed on the saw-cut surface.
5. The determination of the surface percentage of soil inclusions consists in the calculation of the amount of assigned (black) inclusions and the total surface of the saw-cut using IPT.

(B) The methodology to calculate the line percentage of soil inclusions involves three processing steps. The steps 1 and 2 are similar to those of methodology A.

3. Parallel lines with an interdistance of minimum 7 cm are drawn on the deep mix material. The cumulative length of soil inclusions along the line is manually measured. The line percentage is calculated as the proportion of this cumulative length to the total line length.

The observed line and surface percentages can be considered as unbiased estimations of the volume percentage of soil inclusions in the DSM material (Weibel, 1980).

Case study: deep mix panel in Knokke (quaternary sand)

In Knokke, a test DSM panel is executed by CSM in quaternary sand. This panel is 0.55 m thick, 2.1 m long and is executed till 4 m depth. The soil inclusions of this panel are quantified by methodology A on saw-cuts and by methodology B on drilled cores.

This panel is sawn five times. The surface percentage of soil inclusions is quantified on the five saw-cuts (method A). As illustrated in Table 1, soil inclusion surface varies between 0.3% and 1.2% of the total saw-cut surface. The weighted average of soil inclusions in the panel is 0.7 vol%.

Table 1. Surface of soil inclusions in the DSM panel of Knokke (CSM, quaternary sand).

Saw-cut	Observed surface (cm²)	Σ surface inclusions (cm²)	Surface inclusions (%)
1	6 188	51	0.8%
2	14 856	72	0.5%
3	15 595	51	0.3%
4	14 104	83	0.6%
5	15 304	183	1.2%

In the same panel, 18 cores (10 cm diameter and 55 cm length) are drilled. On the surfaces of each core, four lines (every 90°) are drawn in the drill direction. Using method B, 3 083 cm of lines are studied. These lines cross 34 cm of soil inclusions. Therefore, the amount of soil inclusions in the panel is estimated as 1.1 vol%.

The small difference between the estimated amount of soil inclusions (method A: 0.7 vol% and method B: 1.1 vol%) is caused by the dispersion of the distribution of soil inclusions in the DSM panel. This difference will be small in comparison with the expected variation of the amount of soil inclusions in different panels of the same site.

Overview of observed soil inclusions in deep mix material

Table 2 gives an overview of the quantified soil inclusions in DSM material executed in situ. In this table, the soil inclusions are quantified using:

1. method A, applied on saw-cuts of in situ executed DSM columns or panels,
2. method A, applied on the saw-cuts of drilled cores of in situ executed DSM columns of panels,
3. method B, applied on the saw-cuts of drilled cores of in situ executed DSM columns of panels.

The amount of soil inclusions depends on the nature of the soil, wherein the deep mix is performed:

- in quaternary of tertiary sands, the amount of soil inclusions in DSM material varies between 0 and 3.5 vol%,
- in silty soils or alluvial clays, it varies between 3 and 10 vol%,
- in clayey soils with organic material (such as peat) or in tertiary (overconsolidated) clays, it can amount up to 35 vol% and higher.

Table 2. Overview of the quantified soil inclusions in DSM material, executed in different types of Belgian soil.

Site	DSM system	Soil	Observed		Inclusions	
			length (cm)	**surface (cm²)**	**Line** (%)	**Surface** (%)
Leuven	CSM panel	Tertiary sand	2619		2.5	
Mol	Column	Quaternary sand	326		0.9	
Knokke	CSM panel	Quaternary sand	992		0.4	
Knokke	CSM panel	Quaternary sand	3083	66047	1.1	0.7
Antwerp	Column	Quaternary sand	3714		3.4	
Nieuwpoort	CSM panel	Quaternary sand	965	2288	0.1	0.6
Brugge	Column	Quaternary sand	3201	4307	2.4	2.2
Oostende	Column	Quaternary sand	1628		0.5	
Neerpelt	Column	Sand	2147	1212	0.6	0.3
Ghent	CSM panel	Sand	542		2.3	
Wilrijk	Column	Sandy silt	910	2204	7.8	3.5
Aalst	CSM panel	Sandy silt	2752		4.2	
Tielt	CSM panel	Silt	669		5.3	
Roeselare	CSM panel	Silt	462		6.9	
Roeselare	CSM panel	Silt		10960		3.1
Oostduinkerk	Column	Silt	1333		7.9	
Limelette	Column	Silt		3117		10
Duffel	CSM panel	Alluvial clay	1145		5.1	
Kattendijksluis	CSM panel	Alluvial clay	3054		3.7	
Knokke	Column	Clay with peat		12229		35
Roeselare	CSM panel	Stiff clay		1132		35

ELASTIC MODULUS OF DEEP MIX MATERIAL

Execution procedure of elastic modulus determination

The laboratory test to determine the elastic modulus (E) is performed in an unconfined way (MFL 250 kN) on in situ cored deep mix samples with a diameter between 85 mm and 115 mm, according to NBN B 15-203. The measurement accuracy of the core diameter is 0.3 mm. The height to diameter ratio is 2. For these tests, a selection is made of cores, visually of better quality, in order to preserve the uniaxial behavior of the tested samples. The elastic modulus is determined in a tangent way by a cyclic loading between 10% ($\sigma_{10\%UCS}$) and 30% ($\sigma_{30\%UCS}$) of the estimated unconfined compressive strength (UCS) of the test samples. The loading rate amounts to 2.5 kN/s. The sample deformations (ε) during these loading cycles are measured by three couples of demec points. Once the mean difference of the measured deformation, caused by each cyclic loading, is smaller than 1.10^{-5} strains, the elastic modulus is calculated as the ratio $\frac{(\sigma_{30\%UCS} - \sigma_{10\%UCS})}{(\varepsilon_{30\%UCS} - \varepsilon_{10\%UCS})}$. Thereafter, the loading is continued to determine the uniaxial compressive strength (UCS).

Elastic modulus of deep mix material

The tangent elasticity modulus has been determined on 100 cored DSM samples, according to the test procedure mentioned in the previous paragraph. All the samples are cored in DSM walls, executed on 17 sites, with various soil conditions and execution parameters. The curing time of the tested soil mix samples varies between 14 and 180 days. The aim of the present paragraph is to determine the correlation between the elastic modulus and the UCS of the DSM material in general. The test results are not corrected for the curing time.

Fig. 1 shows the elastic modulus as a function of the UCS of the tested DSM material, without distinction of the soil type. A linear relation between the elastic modulus and the UCS is fitted. Doing so, the best estimated value of the elastic modulus is roughly: E = 1 000 UCS. Lower and higher 5% fractile estimations of the elastic modulus are situated between 620 and 1 460 times UCS respectively. These estimations are only valid for the range 2 MPa < UCS < 30 MPa.

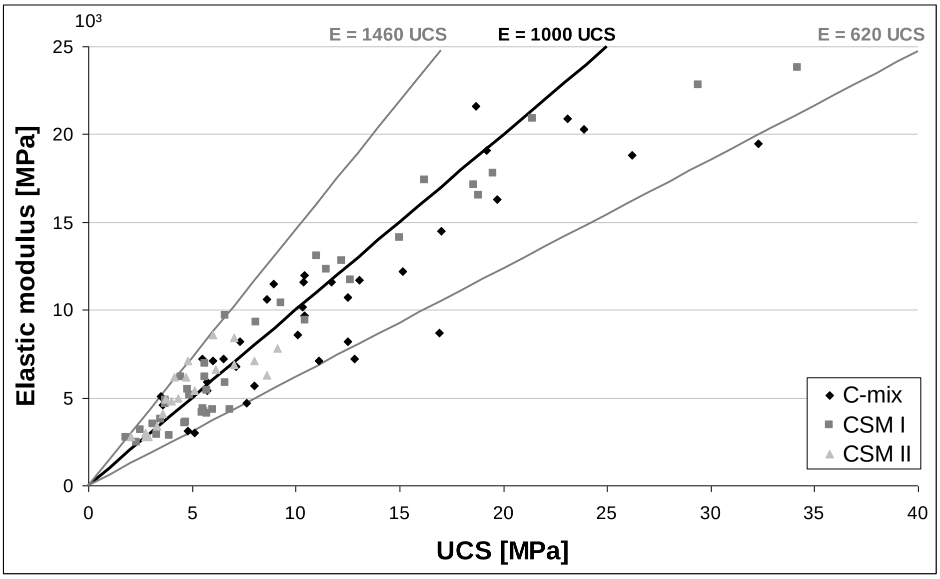

Fig. 1: Elastic modulus [MPa] as a function of the UCS [MPa] for DSM materials executed in different types of soil.

Influence of soil inclusions on the elastic modulus of DSM material

From the various in situ and laboratory observations it is clear that inclusions are always present and that their appearance is relatively different between various sites. The multiple observations allow to derive certain conclusions on the way that their number, size, relative positions, etc. influence the behavior of the material. However, it is not possible to do this in much detail by observations only. That is the reason why the observations and tests are complemented with numerical simulations, whereby sensitivity analyses can be conducted easily. The aim is to conduct elastic and elasto-plastic simulations using a continuous code (FLAC), but also simulating individual fracture growth using a discontinuous code (UDEC). Here, the results of the elastic simulations are presented.

The starting point for the model is a real 2D-section with dimensions of 120 x 240 mm², in which 11 inclusions are observed, corresponding to about 11% surface area. From this, 69 different models were generated, whereby the % surface area of inclusions is changed (by changing the number and size of the inclusions), resulting in 1, 5, 10 and 20% inclusions. Apart from changing the number and size, some of these models contain inclusions with a more rounded shape or one with sharper corners. In Figure 2, the mesh of a 10% model with the original shape and size of the inclusions is presented.

The mixed part in each model corresponds to a Young's modulus E and a Poisson's ratio of respectively 11.6 10^3 MPa and 0.3, while for the soil inclusions these values are 165 MPa and 0.4. The resulting Young's moduli for the entire models are presented in Figure 3, as a function of the % surface area of soil inclusions. The presence of a mere 1% of weak inclusions results in about a reduction of 3% of the stiffness. The presence of 10% of inclusions results on average to a reduction of 30% of the stiffness. It can also be observed that for a certain percentage the variation in Young's moduli is relatively large, but there is no real overlap between the four percentages considered. For example for 10% inclusions, the E-modulus varies between 7.3 10^3 and 8.9 10^3 MPa, while the smallest value for 5% is 9.4 10^3 MPa and the largest value for 20% is 6.5 10^3 MPa.

The reason for the variation for a fixed percentage is mainly linked to the shape. Sharper corners reduce the Young's modulus more, while more rounded shapes (e.g. circle) reduce it less.

COMPRESSIVE STRENGTH OF DEEP MIX MATERIAL

Execution procedure for UCS determination

The laboratory test to determine the UCS is performed by a MFL 250 kN loading machine according to NBN EN 12390-3. The loading rate amounts to 2.5 kN/s. The core samples have a diameter between 85 mm and 115 mm. The measurement accuracy of the core diameter is 0.3 mm. The height to diameter ratio is 1. The UCS is used as a quality control for the in situ DSM material. Ganne et al. (2010) suggest that the estimation of the characteristic value, assuming a log-normal distribution, gives a more realistic estimation than assuming a Gaussian distribution.

For the moment, it is assumed that working with the 5% lower limit of the strength distribution of the cored material is realistic in further calculations. This value is called the characteristic UCS value. In the current procedure, test samples with soil inclusions > 1/6 of the diameter are rejected, on condition that only a limited number of such samples are present and that in the in situ DSM structure, no soil inclusions larger than 1/6 of its width occur. One aim of the numerical simulations (see above) is to verify and, if necessary, optimize this procedure.

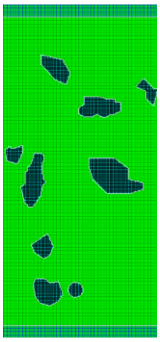

Fig. 2: Mesh of the reference model (10% of surface area is composed of soil inclusions and the original observed shapes are used).

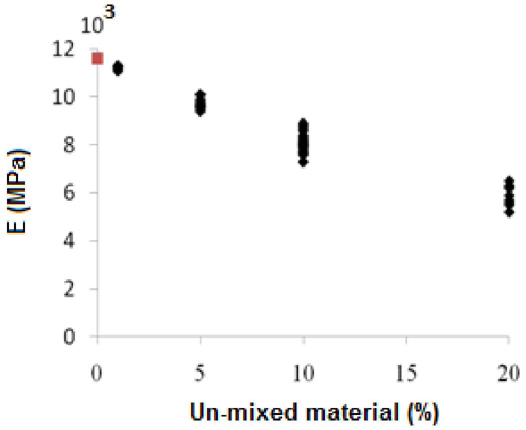

Fig. 3: Variation of the Young's modulus as a function of the percentage surface area corresponding to the soil inclusions.

By conducting numerical simulations, a better understanding should be gained on the size effect between samples and in situ behavior, but also on the size effect of individual inclusions. Is there a difference between many small inclusions or some large ones, both with the same total volume?

Case study: deep mix panel in Knokke

In Knokke, a DSM panel is executed by CSM in quaternary sand. This panel is 0.55 m thick, 2.1 m length and is executed till 4 m depth. Cores (93 mm diameter) are drilled and UCS are measured on 16 samples. Figure 4 gives the histogram of the measured UCS. From these results, a characteristic compressive strength of 7.0 MPa is determined assuming a log-normal distribution.

From the same panel, a bloc with a rectangular base of 53x61 cm and 124 cm high is tested. The vertical deformation is recorded by four LVDT's with a measurement base of 30cm, around the center of each vertical side (see Figure 5.a). The measurement base corresponds roughly to one fourth of the total height. The loading is controlled in displacement. The loading rate is 0.5 mm/min in order to detail the occurrence and growth of the various fractures.

After reaching the peak value, the test is continued to observe the post peak behavior (Figure 6). The maximum strength is 8.3 MPa.

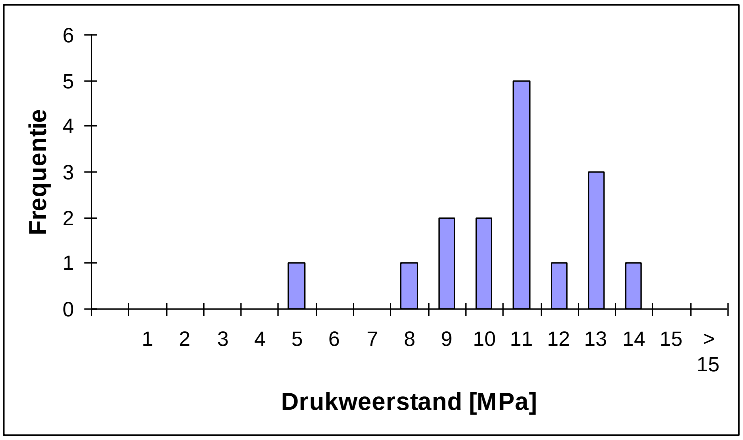

Fig. 4: Histogram of the UCS [MPa] from the cores drilled in the DSM panel of Knokke.

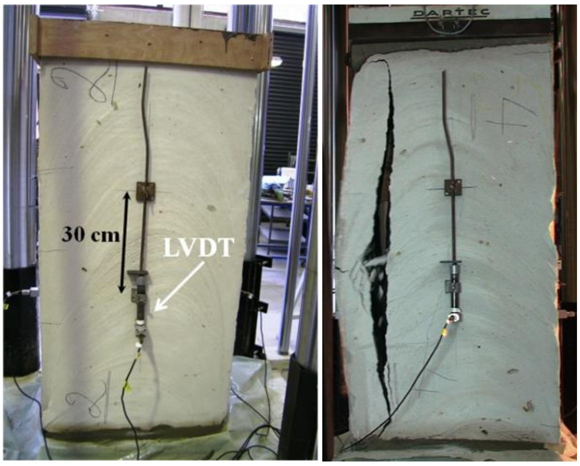

Fig. 5: View of one side of the block, prior to testing (a) & after failure (b).

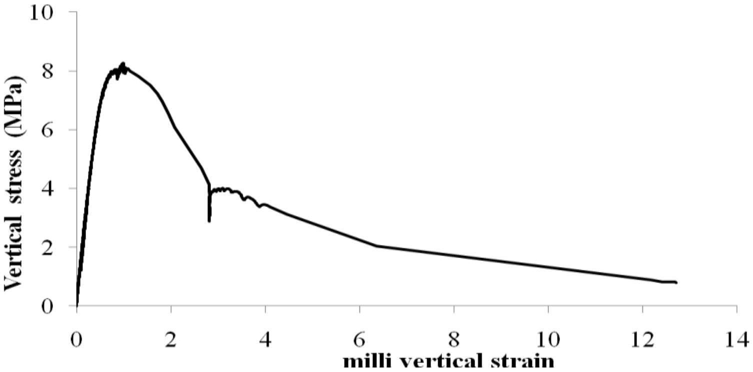

Fig. 6: Stress-strain curve of the tested large bloc.

In comparison with the tested cores, this strength value is at the low side of the recorded values (it coincides well with the characteristic UCS), but one cannot conclude that the large bloc results in a significantly smaller strength (e.g. 2 or 3 times smaller than the average for the cores, as one observes for rock material). This probably means that the DSM panel is relatively homogeneous, in comparison to typical rock material.

Just prior to the peak value, a first macro-fracture is observed on two opposite sides of the bloc. This fracture is vertical and at about 10 cm from one side. Then, it continues to grow along a vertical line and at a strain around 2.6 x 10^{-3}, it results in the spalling of this slab (see Figure 5.b).

CONCLUSIONS

In combination with Ganne et al. (2010), this paper describes the advancement of a current extended research program on DSM material in Belgium (BBRI, 2009-2013).

Based on numerous tests on in situ DSM material, a good insight has been acquired with regard to strength and stiffness characteristics that can be obtained with different DSM execution procedures in several Belgian soils. A methodology to determine the strength and stiffness characteristics of DSM material has been proposed and validated. Numerical simulations have been conducted. They clearly highlight the influence of the amount and the characteristics of soil inclusions on the strength and stiffness characteristics of DSM material.

Within this research program, the tests to determine strength characteristics and numerical simulations will continue. In parallel, numerous tests dealing with permeability, long term behavior (e.g. creep), and adherence with steel reinforcement have been launched. Durability aspects of soil mix material will be treated in the second half of the research program.

Based on the results of the research program, a design methodology for the soil mix structures, accounting for the presence of the heterogeneities and soil inclusions, the scale effects and the time effects such as curing time and creep shall be developed.

REFERENCES

BBRI. (2009). SOIL MIX in constructieve en permanente toepassingen – Karakterisatie van het materiaal en ontwikkeling van nieuwe mechanische wetmatigheden IWT 080736 (in Dutch).

Ganne, P., Huybrechts, N., De Cock, F., Lameire, B., Maertens, J. (2010). SOIL MIX walls as retaining structures – critical analysis of the material design parameters, *International conference on geotechnical challenges in megacities, Moscow. 07 – 10.06.2010.*

Weibel, E. R. (1980). Stereological methods. Vol. 2. Theoretical foundations. New York: Academic Press.